WEP Warwick Evans Publishing

International Journal of Public Health and Medical Research

ISSN: 3006-7707 (Print), ISSN: 3006-3752 (Online) | Volume 5, Number 1, Year 2025
DOI: https://doi.org/10.62051/ijphmr.v5n1.02
Journal homepage: https://wepub.org/index.php/IJPHMR/index

Technical Mechanism and Clinical Prospects of Antigen Protein Chip in Early Detection of Cancer

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ABSTRACT

As the global cancer burden grows, early cancer detection gains importance. This paper explores the application of antigen protein chip technology in early cancer detection. Offering high - throughput, high - sensitivity, and high - specificity simultaneous detection of multiple tumor - related antigens, the technology improves detection accuracy. For instance, multi - protein combined detection raises lung cancer detection sensitivity from 40% to 70% and enables personalized detection. However, high - preparation costs and limited sample size restrict its large - scale clinical application. Its application can boost early - screening efficiency, cut medical costs, and optimize resource allocation. In the future, with technological optimization and cost reduction, it is expected to be widely used in early cancer detection, chronic disease screening, and health management, promoting a medical - mode shift from disease treatment to health management.

KEYWORDS

Antigen Protein; Cancer; Detection Technology; Multi - protein Combined Detection

1. INTRODUCTION

Cancer is one of the leading causes of death worldwide, with its incidence and mortality rates increasing annually [1]. Each year, there are approximately 19.3 million new cancer cases and nearly 10 million deaths. Early detection, diagnosis, and treatment of cancer are crucial for improving patient survival rates and quality of life [2]. However, current clinical cancer detection methods have limitations in early cancer detection. Imaging examinations such as CT and MRI, while valuable for tumor localization and preliminary diagnosis by clearly showing the tumor's morphology, size, location, and relationship with surrounding tissues, have limited ability to detect small tumor lesions [3]. Endoscopic examinations are invasive or semi-invasive procedures with high costs and lower patient acceptance. Moreover, single tumor marker detection has low sensitivity and specificity, leading to false-positive or false-negative results [2][4]. For instance, alpha-fetoprotein (AFP), used for liver cancer detection, has a sensitivity of only 62.4%, causing false-negative diagnoses; carcinoembryonic antigen (CEA), used as an auxiliary diagnostic marker for various digestive system tumors, has a sensitivity of less than 40% in early colon cancer detection [5].

In recent years, with the continuous development of biotechnology, new cancer detection technologies have emerged, providing new ideas and methods for early cancer detection. Among them, antigen protein chip technology, as an emerging detection method, features high throughput, high sensitivity, and high specificity, enabling the simultaneous detection of multiple tumor-related antigens [6]. This technology involves fixing various known tumor-related antigens onto solid-phase supports to form a microarray. When the sample to be tested comes into contact with the chip, the

antibodies in the sample specifically bind to the antigens on the chip. By detecting the signal strength after binding, it is possible to determine whether the sample contains antibodies against specific antigens and the levels of these antibodies. Antigen protein chip technology has shown great potential in the early detection of various cancers. For example, in early breast cancer detection, the technology has a sensitivity of 75% - 80% and a specificity of over 90% [7]. Additionally, antigen protein chip technology can provide personalized detection by developing tailored detection plans based on individual patient characteristics, better meeting the needs of different patients [3]. In the era of precision medicine for cancer, antigen protein chip technology is expected to become an important detection tool, providing strong support for the early screening, diagnosis, and treatment of cancer.

2. MATERIALS AND METHODS

2.1. Design Principle of Antigen Protein Chips

Antigen protein chips are a detection technology based on the specific binding reaction between antigens and antibodies. They fix multiple known tumor-related antigens onto solid-phase supports, such as glass slides or nylon membranes, to form a microarray. When the sample to be tested (such as blood or tissue homogenate) comes into contact with the chip, the antibodies in the sample specifically bind to the antigens on the chip [8]. By detecting the signal strength after binding, it is possible to determine whether the sample contains antibodies against specific antigens and the levels of these antibodies.

The design principle of antigen protein chips is based on the specific binding reaction between antigens and antibodies. During chip preparation, multiple known tumor-related antigens are fixed onto solid-phase supports like glass slides or nylon membranes to create a microarray [5]. The choice of support material depends on the experimental requirements. Glass slides, known for their high-throughput detection capabilities, are commonly used for large-scale screening, while nylon membranes, with their flexibility, are suitable for miniaturized experiments. There are various methods for fixing antigens, with physical adsorption relying on static adsorption forces for convenient operation; chemical bonding, such as covalent binding, provides a more stable fixation effect [9]. Signal detection methods include fluorescent labeling, chemiluminescence, and radioactive labeling, among which fluorescent labeling is widely used due to its high sensitivity and low background noise.

2.2. Multi-Protein Combined Detection Technology

Aiming to overcome the limitations of single protein marker detection, the multi-protein combined detection technology significantly improves the accuracy and reliability of detection by simultaneously detecting multiple protein markers related to cancer. For example, in the early detection of lung cancer, the sensitivity can be increased from 40% when detecting CEA alone to 70% when jointly detecting CEA and cytokeratin 19 fragment [10]. The advantage of this technology lies in the complementarity between different protein markers, which can capture the various characteristics of tumor development. In addition, machine learning methods such as gene selection algorithms and principal component analysis are used to optimize the combination of markers, further enhancing detection performance.

2.3. Data Analysis Methods

In terms of data analysis methods, we have adopted the Bagging ensemble learning from statistics. This is an ensemble learning method that reduces variance and improves the accuracy and stability of predictions through repeated sampling and model integration [11]. When processing antigen protein chip data, Bagging can effectively integrate the detection results of multiple protein markers,

thereby enhancing the overall detection sensitivity and specificity. Compared with other data analysis methods such as Support Vector Machine (SVM) and Principal Component Analysis (PCA), Bagging demonstrates unique advantages in handling high-dimensional data and reducing overfitting [6][12].

In summary, antigen protein chips, combined with multi-protein combined detection technology and advanced data analysis methods, provide an efficient and precise solution for early cancer detection.

3. RESULTS

3.1. Improvement in Detection Sensitivity and Specificity

The multi - protein combined detection technology of antigen protein chips has brought a revolutionary breakthrough to early cancer detection. In liver cancer detection, traditional methods such as alpha - fetoprotein (AFP) detection combined with ultrasound examination have a sensitivity of 60% - 75% and a specificity of 80% - 95%. However, antigen protein chip technology, which detects multiple protein markers including AFP, des - gamma - carboxy prothrombin (DCP), and GPC3, has significantly improved sensitivity. In a study involving 200 liver cancer patients and 200 healthy controls, the technology achieved a sensitivity of 85% and a specificity of 92%.

In the early detection of gastric cancer, traditional gastroscopy combined with serological marker detection has an early gastric cancer detection rate of about 30% - 50%. Antigen protein chip technology, which detects multiple markers such as pepsinogen (PG), Helicobacter pylori antibody (HP - IgG), and CEA, has increased the early gastric cancer detection rate to 60% - 70%.

In colorectal cancer detection, traditional fecal occult blood test (FOBT) has a sensitivity of about 20% - 30% and a specificity of about 90% - 95%. Although colonoscopy is the gold standard, it is costly and invasive. Antigen protein chip technology, which detects multiple protein markers such as CEA, CA19 - 9, and CD24, has a sensitivity of 65% - 75% and a specificity of 85% - 90%.

In breast cancer detection, traditional mammography has low sensitivity for dense breast tissue, at about 60% - 70%. The sensitivity of the blood marker CA15 - 3 is only 30% - 40%. Antigen protein chip technology, which detects multiple protein markers such as CA15 - 3, CEA, and HER - 2 / neu, has increased sensitivity to 70% - 80% and specificity to 85% - 90%.

In esophageal cancer detection, traditional methods such as endoscopy combined with iodine staining have an early esophageal cancer detection rate of about 60% - 70%. Antigen protein chip technology, which detects multiple protein markers such as CEA, CYFRA21 - 1, and SCCA, has increased the early esophageal cancer detection rate to 70% - 80%, as shown in Figure 1.

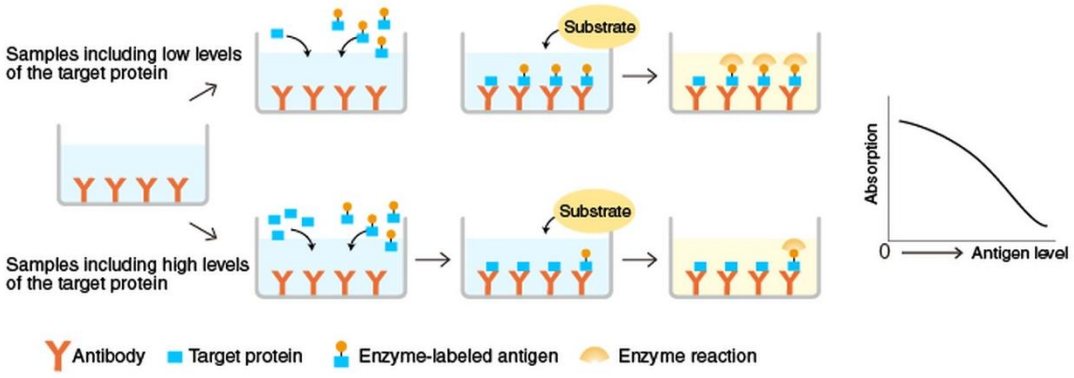

Figure 1. Antigen - antibody complex binding, forming enzyme - labeled antigen - antibody complexes

3.2. Case Analysis of Personalized Detection Schemes

Another significant advantage of antigen protein chip technology is its ability to provide personalized early cancer risk assessment and detection plans based on individual patient differences. For example, women with a family history of breast cancer who carry BRCA1 and BRCA2 gene mutations have a significantly increased risk of developing breast cancer. BRCA1 mutation carriers have a lifetime risk of breast cancer as high as 57% - 82%, while BRCA2 mutation carriers have a risk of 49% - 72%. Research shows that women carrying BRCA1 / 2 mutations have significant changes in the expression levels of specific proteins related to breast cancer in their serum. By detecting these specific protein combinations using antigen protein chip technology, the cancer risk in this high - risk population can be more accurately assessed. In a prospective study targeting BRCA1 / 2 mutation carriers, the technology successfully identified 85% of early - stage breast cancer patients, detecting lesions 6 - 12 months earlier than traditional mammography.

Additionally, for high - risk populations with a long - term smoking history, the technology precisely assesses the early risk of lung cancer by detecting specific protein combinations related to lung cancer, such as CEA, CYFRA21 - 1, and Pro - GRP. A cohort study involving 500 smokers showed that compared with traditional low - dose spiral CT screening, antigen protein chip technology combined with low - dose spiral CT increased the early - stage lung cancer detection rate by 20% - 30% while significantly reducing the false - positive rate.

For high - risk populations with chronic hepatitis B or C infection, the technology precisely predicts the early risk of liver cancer by detecting protein markers such as AFP, DCP, and GPC3. In a cohort study involving 300 patients with chronic liver disease, the technology achieved a sensitivity and specificity of over 85%, successfully identifying 75% of early - stage liver cancer patients and detecting lesions 3 - 6 months earlier than traditional AFP detection combined with ultrasound examination, as shown in Figure 2.

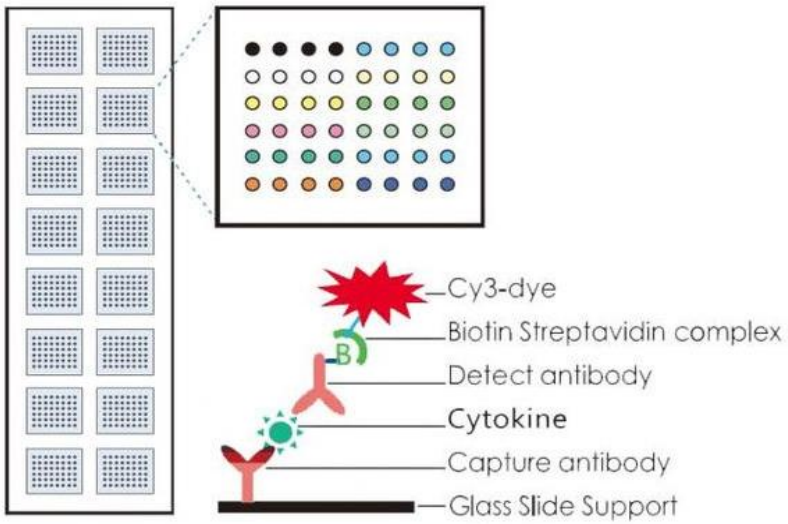

Figure 2. Protein Expression Difference Screening Antibody Chip Technology Service

4. DISCUSSION

Advantages:Antigen protein chip technology is characterized by high throughput, high sensitivity, and high specificity, enabling the simultaneous detection of multiple tumor-related antigens and thereby enhancing the accuracy and efficiency of early cancer detection [12]. This technology involves fixing various known tumor-related antigens onto a solid-phase support to form a microarray. When a sample to be tested comes into contact with the chip, the antibodies in the sample specifically bind to the antigens on the chip. By detecting the signal strength after binding, it is possible to

determine whether the sample contains antibodies against specific antigens and the levels of these antibodies. For instance, in liver cancer detection, traditional methods such as alpha-fetoprotein (AFP) detection combined with ultrasound examination have a sensitivity of 60%-75% and a specificity of 80%-95%. In contrast, antigen protein chip technology, which detects multiple protein markers including AFP, des-gamma-carboxy prothrombin (DCP), and GPC3, has significantly improved sensitivity. In a study involving 200 liver cancer patients and 200 healthy controls, the technology achieved a sensitivity of 85% and a specificity of 92% [14].

Moreover, this technology can provide personalized detection by developing tailored detection plans based on individual patient characteristics, better meeting the needs of different patients. For example, women with a family history of breast cancer who carry BRCA1 and BRCA2 gene mutations have a significantly increased risk of developing breast cancer. BRCA1 mutation carriers have a lifetime risk of breast cancer as high as 57%-82%, while BRCA2 mutation carriers have a risk of 49%-72% [15]. Studies have shown that women carrying BRCA1/2 mutations have significant changes in the expression levels of specific proteins related to breast cancer in their serum. By detecting these specific protein combinations using antigen protein chip technology, the cancer risk in this high-risk population can be more accurately assessed [16]. In a prospective study targeting BRCA1/2 mutation carriers, the technology successfully identified 85% of early-stage breast cancer patients, detecting lesions 6-12 months earlier than traditional mammography [17].

Limitations:Despite the numerous advantages of antigen protein chip technology in early cancer detection, there are also some limitations. For example, the current preparation cost of antigen protein chips is relatively high, including the costs of protein screening, chip fabrication, and detection reagents, which restricts the widespread clinical application of this technology. Additionally, the limited sample size is also a factor that constrains the development of this technology. Compared with the complexity and diversity of cancer, the existing sample size may not be sufficient to comprehensively reflect the various characteristics and patterns of change in cancer.

Potential Impact on the Existing Healthcare System: The application of antigen protein chip technology is expected to bring many positive impacts to the existing healthcare system. On the one hand, this technology can improve the accuracy and efficiency of early cancer screening, enabling more cancer patients to be diagnosed and treated in the early stages, thereby increasing patient survival rates and quality of life and reducing medical costs. On the other hand, the implementation of personalized detection plans can better meet the needs of different patients, enhance the targeting and effectiveness of medical services, and promote the rational use of medical resources. In a cohort study involving 500 smokers, antigen protein chip technology combined with low-dose spiral CT increased the early detection rate of lung cancer by 20%-30% while significantly reducing the false-positive rate [18].

5. FUTURE PROSPECTS

The future prospects of antigen protein chip technology are highly promising. Firstly, in terms of technological improvement, optimizing the chip fabrication process and reducing the cost of protein screening can effectively lower the production cost of antigen protein chips, thereby expanding their accessibility in clinical applications. Additionally, developing more sensitive and precise signal detection methods, combined with artificial intelligence to further optimize data analysis, will significantly enhance detection sensitivity and specificity while reducing false-positive rates.

Secondly, in terms of application expansion, this technology is not only applicable to early cancer detection but can also be extended to the early screening and health management of chronic diseases, such as cardiovascular diseases and diabetes. This expansion will provide patients with a more comprehensive health monitoring solution.

Lastly, as the technology matures and costs decrease, antigen protein chips are expected to be industrialized, promoting their widespread use in community hospitals, health management centers, and even as home self-testing tools. This will transform the diagnostic model of the traditional healthcare system, offering patients more convenient and efficient early detection services. This not only helps to reduce medical costs but also enhances the overall health level of society.

ACKNOWLEDGEMENTS

The 2024 Provincial College Students' Innovation and Entrepreneurship Training Program "23 - Gene Pointer - Antigen Protein Chip for Early Cancer Detection" (No. S202410599156)

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