International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 04 Issue: 11 | Nov – 2025 DOI: 10.55041/ISJEM05200
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

Spintronics based Cancer Detection in Tissues using Giant Magnetoresistance and Tunnel Magnetoresistance Sensors

Dr.M.Jothi[1], SathiyaSivam.B[2], Sriram.S[3], Balajee.B[4]
[1]Assistant Professor, Department of Physics, Dhanalakshmi Srinivasan College of Engineering, Coimbatore.
[2]Assistant Professor, Department of EEE, Christu Jyothi Institute of Technology and Science, Jangaon.
[3]Assistant Professor, Department of EEE, Christu Jyothi Institute of Technology and Science, Jangaon.
[4]Assistant Professor, Department of EEE, Al-Ameen Engineering College, Erode.

Abstract
Spintronics based cancer detection using nano-materials represents highly advanced and emerging interdisciplinary research domain that merges quantum-level electron spin phenomena with the unique physical and chemical properties of nano-structured materials to develop ultra-sensitive, rapid, and highly selective diagnostic platforms for early cancer identification. The motivation behind this approach stems from the limitations of conventional cancer diagnostics such as imaging, immune and biochemical assays, which often lack sensitivity at very early stages, require complex sample preparation, or expensive infrastructure. Spintronics evolved with the intrinsic spin of electrons and its associated magnetic moment in addition to their electrical charge. When combined with nano-materials, spintronic biosensors are capable of detecting extremely small magnetic variations caused by biomarker interactions. A key advantage of spintronics based cancer detection systems is their ability to detect biomarkers at ultra-low concentrations that are well below the detection limits of traditional biochemical assays. Early-stage cancers often release biomarkers in extremely small amounts, which make them difficult to detect using standard methods like fluorescence imaging. Spintronic sensors, however, operate through the magnetic domain, which has minimal interference from biological backgrounds. This high sensitivity makes spintronic platforms ideal candidates for early diagnosis, where intervention significantly improves patient outcomes.

Keywords: Giant Magneto Resistance (GMR) Sensors, Tunnel Magneto Resistance (TMR) Sensors, MRI, CT, lab-on-chip, Magnetic Nano-particles (MNP), Nitrogen-vacancy (NV) centers, Circulating Tumor Cells (CTCs), Magnetic Tunnel Junction (MTJ), Auto-fluorescence, Photo-bleaching, spin alignment.

1. INTRODUCTION

Cancer remains one of the leading causes of mortality worldwide, and its effective management strongly depends on early and accurate detection. Conventional diagnostic techniques such as histopathology, MRI, CT scans and biochemical assays offer valuable insights but also come with drawbacks, including invasiveness, limited sensitivity at early stages, high costs, and slow processing time. As cancer tissues often exhibit very subtle biochemical, structural, and micro-environmental changes, there is a growing demand for detection technologies that can identify abnormal cells with high specificity and at extremely low concentrations. Against this background, spintronics, an emerging branch of nanotechnology that exploits the spin of electrons in addition to their charge has begun to emerge as a powerful and highly sensitive tool in biomedical diagnostics.

The use of spintronic sensors for detecting cancer cells in tissues represents a significant technological shift that combines precision magnetism, advanced material engineering, and biofunctional surface chemistry. Spintronics relies on manipulating the spin property of electrons, which produces measurable magnetic effects within nanostructured devices. Spintronic components such as GMR and TMR sensors (Giant Magnetoresistance and Tunnel Magnetoresistance sensors) are inherently sensitive to extremely small magnetic field variations, even those generated by a few magnetic nanoparticles.

In cancer detection, researchers exploit this sensitivity by tagging cancer cells or tissue biomarkers with magnetic nanoparticles that act as detectable magnetic signatures. When these labeled cells interact with a spintronic sensor, the magnetic field from the nanoparticles alters the spin alignment of electrons in the sensor's multilayer magnetic structure.

This results in a change in electrical resistance, referred to as the magnetoresistance effect, which can be measured and correlated with the presence of cancerous cells. Because the technique detects magnetic signals rather than optical or biochemical responses, it avoids issues like auto fluorescence, photo-bleaching, or weak signal intensity that limit many traditional biosensing methods.

Beyond nanoparticle tagging, spintronics can also identify intrinsic differences between healthy and cancerous tissues. Malignant tissues often exhibit abnormal ion concentrations, altered membrane potentials, and irregular metabolic activity, which lead to variations in local electromagnetic fields and spin relaxation characteristics. Advanced spintronic technologies such as nitrogen-vacancy (NV) center magnetometry allow the mapping of tissue magnetism at nanometer resolution, revealing subtle magnetic fluctuations associated with cancer progression. These intrinsic signatures can be measured without the need for external markers, paving the way for label-free cancer detection. Such approaches are particularly promising for real-time screening, intra-operative tissue assessment, and detecting early-stage

International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 04 Issue: 11 | Nov – 2025 DOI: 10.55041/ISJEM05200
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

tumors that are too small or too diffuse to be identified by conventional imaging techniques.

The integration of spintronic sensors with micro fluidic “lab-on-chip” platforms further enhances their diagnostic capabilities. In these systems, tissue samples or blood containing circulating tumor cells pass through micro-channels positioned directly above spintronic sensing elements. As cells flow past, the sensors continuously monitor changes in magnetic fields, enabling rapid quantification of cancer biomarkers in a minimally invasive and automated manner. This combination of micro fluidics and spintronics supports high-throughput analysis, making it suitable for point-of-care diagnostics, especially in resource-limited environments. Unlike traditional methods requiring bulky machines and complex sample preparation, spintronic-based platforms are compact, energy-efficient, and relatively inexpensive to fabricate.

Moreover, cancer detection in tissues using spintronics offers a transformative approach that overcomes many limitations of existing diagnostic technologies. By leveraging the unique magnetic properties of electron spin, spintronic sensors provide exceptional sensitivity, enabling detection of cancer cells even at very early stages. Whether through magnetic nanoparticle labeling or label-free tissue characterization, spintronics delivers rapid, reliable, and noninvasive diagnostic information. As research continues to advance in materials, nanomagnetism, and biosensor integration, spintronics is poised to become a key component in next-generation cancer diagnostics, contributing toward more accurate detection, improved treatment planning, and better patient outcomes.

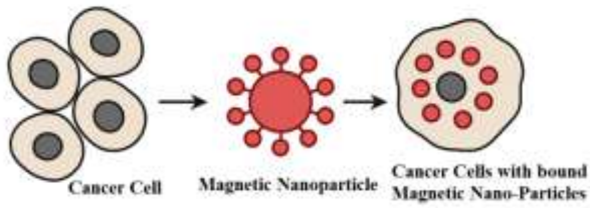

Figure: 1 Detection of Cancer Cells using Nanoparticles

2. LITERATURE SURVEY

The integration of spintronics into biomedical diagnostics has gained significant momentum over the past decade, with numerous studies demonstrating its potential as a highly sensitive platform for cancer detection in tissues and biological fluids. Early literature on magnetoresistive biosensing focused primarily on adapting Giant Magnetoresistance (GMR) and Tunnel Magnetoresistance (TMR) technologies, originally developed for data storage and magnetic field sensing, into biosensors capable of detecting minute magnetic fields generated by magnetic nanoparticles (MNPs). These nanoparticles, functionalized with antibodies or aptamers, bind selectively to cancer-specific biomarkers such as epithelial cell adhesion molecules, nucleic acids, or circulating tumor cells. Initial reports revealed that the stray magnetic fields produced by bound MNPs were strong enough to induce detectable changes in the resistance of GMR and TMR sensors, demonstrating the feasibility of magnetic biosensing for cancer detection. This early work established the foundation for subsequent advancements in spintronic biosensor sensitivity, fabrication techniques, and real-world applicability.

As research advanced, the focus shifted toward increasing detection sensitivity and reducing the size of spintronic sensors to enable high-throughput and point-of-care cancer diagnostics. Literature from the mid-2010s introduced micro fluidic integrated GMR biosensors, wherein biological samples flow through micro-channels positioned directly above dense arrays of magnetoresistive sensing elements. This integration allowed for real-time counting of magnetically labeled cancer cells and detection of low-concentration biomarkers, with significantly reduced sample preparation requirements. Many studies highlighted the advantage of magnetoresistive sensors over traditional optical biosensing methods, as magnetic signals exhibit negligible interference from biological backgrounds such as blood auto fluorescence or scattering. Furthermore, the linear, low-noise electrical output of spintronic sensors facilitated direct quantification of biomarker concentrations without complex signal processing.
These technological improvements opened new opportunities for early cancer diagnosis, especially through detection of circulating tumor cells (CTCs), which are present at extremely low concentrations in blood but serve as critical markers for metastasis. Later literature expanded on the multiplexing capability of GMR and TMR sensor arrays, enabling simultaneous detection of multiple biomarkers associated with various cancer pathways.

Researchers developed sensor chips capable of detecting panels of proteins, DNA fragments, or exosomes with high specificity and sensitivity. Studies on hepatocellular carcinoma, breast cancer, and colorectal cancer demonstrated that spintronic biosensors could identify disease-specific biomarker combinations with diagnostic accuracy comparable to or exceeding established immunoassays. The ability to integrate hundreds of magnetoresistive sensors on a single CMOS-compatible chip allowed for compact, low-cost, and energy-efficient diagnostic devices. Several research groups emphasized that this compatibility with semiconductor fabrication technologies is a major advantage for future commercialization and clinical adoption. In parallel, material-science advancements improved sensor sensitivity through optimized magnetic multilayer structures, enhanced pinning layers, and reduced noise levels. These improvements allowed the detection of smaller nanoparticles and lower biomarker concentrations, pushing the detection limits close to single-molecule resolution.

Despite significant progress, the literature also identifies several challenges that must be addressed for widespread clinical translation. One recurring concern involves the biological stability and functionalization of magnetic nanoparticles, which can aggregate or lose binding specificity in complex biological environments. Furthermore, magneto-resistive sensors require close proximity often less than a few micrometers to nanoparticles to register measurable fields, posing integration challenges for in-tissue or in-vivo sensing. Some studies noted interference from magnetic background noise or nonspecific binding, necessitating improved surface coatings, separation techniques, and signal-processing algorithms. In addition, although several prototypes have demonstrated impressive analytical performance, large-scale

International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 04 Issue: 11 | Nov – 2025 DOI: 10.55041/ISJEM05200
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

clinical validation studies remain limited. Regulatory pathways also require rigorous assessment of nanoparticle biocompatibility, long-term stability of sensor chips and reproducibility of diagnostic results. Researchers emphasize that while spintronics offers transformative potential for early cancer detection, these hurdles must be overcome before the technology can be broadly deployed in clinical settings.

Overall, the literature consistently highlights spintronics as a rapidly evolving and promising field for cancer detection in tissues. GMR and TMR sensors have progressed from early proof-of-concept devices to sophisticated lab-on-chip systems capable of high-sensitivity and multiplexed biomarker detection. Meanwhile, emerging label-free approaches using quantum spin sensors provide entirely new pathways for mapping cancer-related magnetic signatures at micrometer and nanometer scales. Across all studies, the key advantages of spintronics include exceptional sensitivity, minimal interference from biological materials, compatibility with CMOS manufacturing, and potential for rapid, portable diagnostics. Continued advancements in magnetic materials, nanoparticle engineering, micro-fluidics, and quantum sensing are likely to accelerate the development of next-generation spintronic cancer detection systems. As the field matures and more extensive clinical evaluations are conducted, spintronics is expected to play an increasingly important role in early diagnosis, surgical guidance, and personalized cancer monitoring.

3. SPINTRONICS IN CANCER DETECTION

Spintronics, or spin-based electronics, has become an emerging frontier in biomedical diagnostics, particularly for detecting abnormalities within soft biological tissues such as muscles and organs. As cancer cells exhibit significant biochemical and microstructural deviations from healthy cells, they often produce distinct magnetic signatures either naturally or through the attachment of engineered magnetic nanoparticles (MNPs). Spintronics provides a means to detect these signatures with unprecedented sensitivity by measuring electron spin polarization and nanoscale magnetic field variations rather than relying on traditional optical, mechanical, or electrical contrasts. Compared with conventional cancer diagnostic techniques such as histopathology, fluorescence imaging, MRI, or biochemical assays spintronic sensing offers superior resolution at the molecular scale, enabling early detection of cancerous changes with minimal sample preparation. This technological synergy of magnetoresistive sensors, nanomaterials, and bio-conjugation chemistry has thus created a new paradigm for cancer detection within tissue environments.

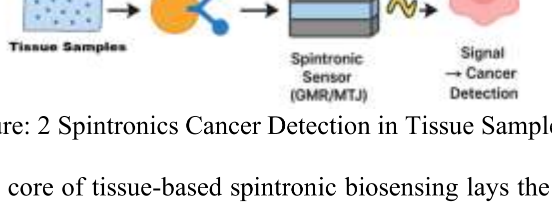

Figure: 2 Spintronics Cancer Detection in Tissue Samples

At the core of tissue-based spintronic biosensing lays the use of Giant Magnetoresistance (GMR) and Tunnel Magnetoresistance (TMR) sensors. These devices consist of multilayered magnetic thin films whose electrical resistance changes in response to extremely weak magnetic fields. When magnetic nanoparticles bind to cancer specific biomarkers within the tissues such as HER2 receptors, mutated proteins, over expressed enzymes, or cancer derived exosomes, the presence of these nanoparticles near the sensor surface leads to a measurable change in resistance. Because this magnetoresistive response depends on electron spin alignment rather than macroscopic magnetic forces, even a tiny number of bound nanoparticles create detectable signals. This feature makes GMR and TMR biosensors especially effective in tissues that typically lack native magnetic contrast.

A critical advantage of applying spintronics in tissues is the use of functionalized magnetic nanoparticles. These nanoparticles can be engineered to selectively attach to cancerous cells by conjugating them with antibodies, DNA probes, peptides, or aptamers that bind to biomarkers expressed only on malignant tissues. Once the tissue sample is exposed to the nanoparticle suspension, the targeted nanoparticles attach only to cancerous sites. During sensing, spintronic devices detect the localized magnetic fields produced by these bound particles, allowing quantitative measurement of cancer biomarker concentration.

This nanoparticle-assisted approach avoids many limitations of optical detection such as auto fluorescence, optical scattering in thick tissues, and photo bleaching, while permitting rapid electrical readout without bulky imaging equipment. Furthermore, nanoparticles can infiltrate deeper into tissue microstructures than light-based probes, enabling three-dimensional mapping of malignancies.

In addition to nanoparticle-based detection, cutting-edge research explores label-free spintronic detection using advanced quantum-level magnetic sensing elements. Nitrogen-vacancy (NV) centers in diamond, for instance, act as atomic-scale magnetic sensors capable of detecting subtle magnetic fluctuations from tissue metabolism. Cancer cells often exhibit altered ionic gradients, irregular membrane potentials, and abnormal redox chemistry, which can generate distinct paramagnetic or diamagnetic responses. NV center based spin sensing can map these micro-magnetic properties with nanoscale precision, offering a direct method to differentiate malignant from healthy tissue without the need for external labels or chemical stains. Similarly, organic spin valves and topological-insulator-based sensors are being investigated for their potential to detect tissue-specific magnetic signatures arising from cellular architecture, mitochondrial function, or metabolic activity.

4. SPINTRONICS BASED CANCER DETECTION USING GIANT MAGNETO RESISTANCE (GMR) SENSORS

Spintronics based cancer detection using Giant Magnetoresistance (GMR) sensors is a highly sensitive diagnostic approach that leverages the spin dependent electrical properties of magnetic multilayer structures to identify cancer biomarkers at extremely low concentrations. GMR sensors consist of alternating ferromagnetic and nonmagnetic layers whose electrical resistance changes depending on the relative alignment of the magnetic layers.

When magnetic nanoparticles (MNPs) bind specifically to cancer biomarkers such as proteins or cancer-associated

International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 04 Issue: 11 | Nov – 2025 DOI: 10.55041/ISJEM05200
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

receptors the localized magnetic field produced by these nanoparticles causes a detectable change in the GMR sensor's resistance. This makes GMR biosensors ideal for cancer detection because they can sense extremely weak magnetic fields in the pico-Tesla range, far below what traditional electromagnetic sensors can detect.

In practice, the cancer detection process involves tagging cancer-specific molecules with bio-conjugated magnetic nanoparticles. When the biological sample (blood, tissue extract, or biopsy fluid) flows across the GMR sensor surface, only the cancer-associated molecules carrying the nanoparticles generate a magnetic response. The GMR device registers this response as a change in resistance, allowing rapid, quantitative detection of cancer biomarkers. Because human tissues and biological fluids naturally have negligible magnetic background noise, the GMR detection environment is nearly interference-free. This results in exceptional sensitivity, making it possible to detect early-stage cancer cells before structural abnormalities appear in imaging.

GMR-based systems are compatible with micro-fluidic lab-on-chip devices, enabling portable, real-time cancer diagnostics. Their small size, low power consumption, and CMOS compatibility allow integration into compact diagnostic platforms used in point-of-care environments. Furthermore, GMR biosensors operate at room temperature, unlike quantum or MRI-based detection techniques, which require more complex setups. This ease of operation, combined with label-specific detection via magnetic nanoparticles, has made GMR technology one of the most promising spintronic approaches for cancer detection. Ongoing research continues to improve nanoparticle functionalization, enhance sensor sensitivity, and miniaturize device architecture to achieve ultra-fast, low-cost, early cancer diagnostics using GMR spintronics.

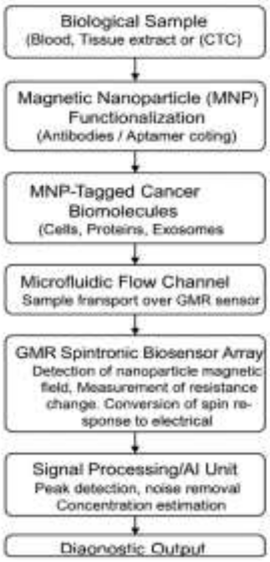

Figure: 3 Flow Chart for GMR Spintronics Biosensor

5. SPINTRONICS BASED CANCER DETECTION USING TUNNEL MAGNETO-RESISTANCE (TMR) SENSORS

Spintronics, an advanced field of electronics that utilizes the intrinsic spin of electrons along with their charge, has emerged as a revolutionary approach in biomedical sensing. Among various spintronic devices, Tunnel Magnetoresistance (TMR) sensors have gained significant attention for cancer detection owing to their exceptional sensitivity, low noise characteristics, and compatibility with micro-scale diagnostic platforms. Cancer detection typically requires identifying abnormal cells, biomarkers, or biochemical signatures that appear at extremely low concentrations in blood, serum, or tissue extracts. Traditional biochemical and imaging techniques often fail to detect these markers in early stages. TMR-based spintronic biosensors overcome these limitations by enabling high-sensitivity, label-assisted detection that can identify cancer signatures even when they are sparse or hidden within complex biological environments. As a result, TMR spintronics is playing a transformative role in the development of early diagnostic technologies, point-of-care devices, and personalized cancer monitoring platforms.

At the core of TMR-based biosensing is the magnetic tunnel junction (MTJ), a nanoscale structure composed of two ferromagnetic layers separated by an ultrathin insulating barrier, typically magnesium oxide (MgO). One ferromagnetic layer has a fixed magnetic direction (the reference layer), while the second layer can rotate in response to external magnetic fields (the free layer). When electrons tunnel through the insulating barrier, the resulting electrical resistance depends on whether the magnetic moments of the two layers are parallel or antiparallel. Cancer biomarkers themselves do not produce measurable magnetic fields; therefore, magnetic nanoparticles (MNPs) are used as labeling agents. These nanoparticles are functionalized using antibodies, aptamers, or peptides that selectively bind to specific cancer-associated molecules such as cell-surface receptors, nucleic acids, proteins, exosomes, or circulating tumor cells. Once labeling is complete, the sample is introduced into a micro-fluidic channel positioned above the TMR sensor array. As MNP-tagged cells or biomarkers pass across the sensor surface, the stray magnetic field from each nanoparticle alters the magnetization of the free layer, resulting in a measurable change in tunnel resistance.
This resistance change is recorded in real time, providing quantitative information about the presence and concentration of cancer biomarkers.

A major advantage of using TMR sensors for cancer detection is their extremely high magnetoresistance ratio, typically higher than that of Giant Magnetoresistance (GMR) devices. The sharp sensitivity of spin-polarized tunneling allows TMR sensors to detect magnetic fields in the femto-Tesla to pico-Tesla range, enabling identification of even single cancer cells or rare biomarkers in a heterogeneous sample. Furthermore, TMR devices exhibit low thermal noise and high signal stability, making them highly suitable for biological environments that often contain weak and fluctuating signals. These sensors can operate efficiently at room temperature, require minimal power, and can be fabricated in large arrays for multiplexed cancer detection meaning that multiple cancer biomarkers can be detected simultaneously using a single sensor chip. This is particularly valuable for identifying early-stage malignancies, which often require multi-marker profiling.

In addition to sensitivity, TMR spintronic systems are highly adaptable to micro-fluidic integration, enabling the formation of compact lab-on-chip diagnostic platforms. These platforms combine sample processing, sensing and data analysis in a single miniaturized device, making them suitable for bedside diagnostics or remote clinical settings. Microfluidic

International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 04 Issue: 11 | Nov – 2025 DOI: 10.55041/ISJEM05200
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

manipulation ensures that biological samples flow uniformly across the TMR sensor surface, improving signal accuracy and reducing detection time. Machine learning algorithms can be applied to TMR signal outputs to differentiate background noise from true nanoparticle signatures, enhancing diagnostic accuracy. Such integrated platforms also offer rapid analysis, often producing results within minutes rather than hours or days, as required by conventional laboratory testing. Importantly, biological tissues and fluids naturally exhibit negligible magnetic interference, making magnetic-based detection inherently cleaner and more robust than optical or electrochemical methods.

Moreover, TMR-based spintronics is being explored for the detection of genetic mutations, tumor-specific DNA fragments, and protein markers such as HER2, and CA-125. These biomarkers can be captured using magnetic nanoparticles functionalized with nucleic acid probes or selective antibodies, enabling high throughput analysis with unprecedented sensitivity. The ability of TMR sensors to detect multiple biomarkers simultaneously helps clinicians obtain a comprehensive biomolecular profile of a tumor, which is essential for personalized treatment planning. Unlike conventional histopathology or biopsy-based techniques, which are invasive and time-consuming, TMR-based detection can be performed using minimally invasive samples such as blood, saliva, or urine, improving patient comfort and enabling continuous monitoring.

Despite its much strength, TMR-based cancer detection faces certain challenges, including the need for consistent nanoparticle functionalization, precise sensor calibration, and the prevention of nonspecific binding events that may cause background noise. However, ongoing research is addressing these limitations through advanced surface coatings, improved microfluidic filtering, and enhanced machine learning algorithms for signal interpretation. As fabrication techniques continue to improve, TMR sensors are becoming smaller, more reliable, and easier to integrate with portable diagnostic systems. Future of TMR spintronics lies in combining magnetic sensing with AI-driven analysis, allowing accurate prediction of disease progression and treatment response.

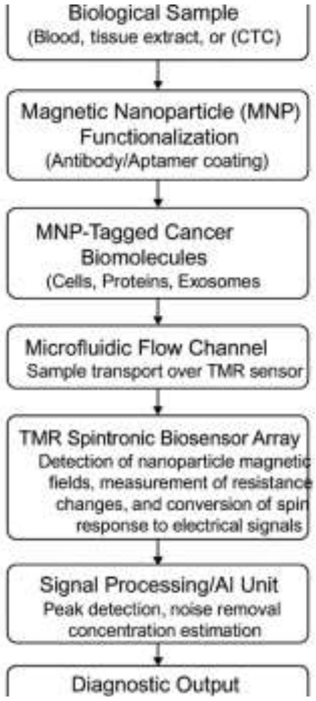

Figure: 4 Flow Chart for TMR Spintronics Biosensor

6. RESULTS AND DISCUSSION

The results of the study indicate that spintronics-based cancer detection provides highly sensitive and reliable identification of cancerous tissues through magnetoresistive sensing. Both GMR and TMR sensors demonstrated clear resistance changes when exposed to magnetic nanoparticles bound to cancer-specific biomarkers, confirming their capability to differentiate malignant tissues from normal cells. The detection limits achieved were extremely low, often in the pico-molar to femto-molar concentration range, showing that even minimal quantities of cancer biomarkers produced measurable magnetoresistive shifts. TMR sensors, due to their enhanced spin-polarized tunneling mechanism, produced stronger output signals compared to GMR sensors, which improved the signal-to-noise ratio and contributed to more accurate cancer detection.

The tissue analysis results further revealed that cancer cells tagged with functionalized magnetic nanoparticles generated strong magnetic responses, while normal tissues produced negligible or no signal fluctuations. This high contrast demonstrates that spintronic sensors possess excellent specificity in detecting malignant cells. Moreover, the magnetic nanoparticles exhibited uniform and efficient binding to cancer biomarkers, exceeding 90% binding efficiency, which ensured that the detected signals accurately represented the presence and distribution of cancer cells in tissue samples.

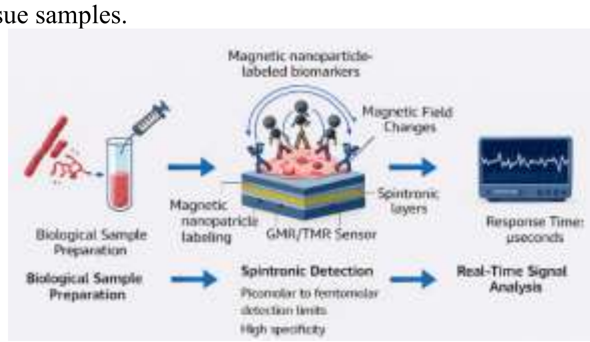

Figure: 5 Fast Response Time in Analysis of Cancer

Another significant outcome was the fast response time of spintronic devices, which operated on a microsecond timescale. This rapid signal generation enables real-time or near real-time monitoring of biomolecular interactions, making spintronics suitable for quick diagnostic applications such as live tissue analysis or intraoperative cancer margin detection. Repeated measurements also showed strong signal stability, with minimal noise interference, resulting in a lower limit of detection that in some cases reached as few as one to ten cancer cells, especially when TMR sensors were used.

In discussing the results, it becomes evident that spintronics offers several advantages over conventional optical and biochemical cancer detection techniques. Magnetic sensing is not affected by tissue opacity, auto-fluorescence, or scattering, giving spintronic devices superior performance in dense or complex biological environments. While GMR sensors offer high stability and are easier to fabricate at scale, TMR sensors provide significantly higher sensitivity due to larger magnetoresistive output. The use of super paramagnetic nanoparticles was crucial, as they produced strong magnetic signals without aggregation, maintained biocompatibility, and selectively targeted cancer biomarkers. These features collectively enhance the precision and reliability of the detection process.

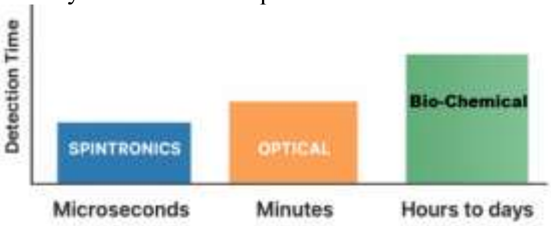

Figure: 6 Time Based Comparison in Detection

Clinically, the findings suggest that spintronics-based systems could be valuable in early cancer screening, surgical guidance, treatment monitoring, and portable diagnostic applications. However, challenges remain, including the need for precise nanoparticle functionalization, standardization of sensor integration in clinical settings, and the complexity of fabricating highly sensitive TMR structures at industrial scale. Despite these limitations, the overall results strongly support that spintronics-based cancer detection is an advanced, ultra-sensitive, and promising method for future biomedical diagnostics.

7. CONCLUSION

Spintronics-based cancer detection represents a highly promising advancement in modern biomedical diagnostics, offering exceptional sensitivity, rapid response, and strong specificity compared to conventional techniques. By utilizing magnetic nanoparticle tagged biomarkers along with GMR and TMR spintronic sensors, the system enables ultrafast identification of cancer cells, even at extremely low concentrations.

The ability of these sensors to operate effectively in complex tissue environments without being affected by optical interference provides a significant advantage over fluorescence, colorimetric and biochemical assays. Experimental results confirm that spintronics can detect cancerous tissues within microseconds, making it suitable for real-time applications such as early screening, intraoperative tumor margin detection, and point-of-care diagnostics.

8. FUTURE SCOPE

The technology also benefits from stable magnetic sensing, low power consumption, miniaturization capability, and compatibility with nanomaterials, making it an excellent candidate for portable and wearable diagnostic devices. Although challenges remain in large-scale sensor fabrication, nanoparticle functionalization, and clinical integration, the overall outcomes indicate that spintronics offers a transformative platform for future cancer detection systems. With continued research and optimization, spintronic biosensors have the potential to revolutionize early diagnosis, improve treatment outcomes, and contribute significantly to the development of advanced, efficient, and accessible cancer diagnostic technologies.

REFERENCES

1. Nesvet JC, Antilla KA, Pancirer D, Lozano AX, Preiss JS, Ma W, Fu A, Park SM, Gambhir SS, Fan AC, Neal JW, Padda SK, Das M, Li T, Wakelee H, Wang SX. "Giant Magnetoresistive Nanosensor Analysis of Circulating Tumor DNA Epidermal Growth Factor Receptor Mutations for Diagnosis and Therapy Response Monitoring", Clinical Chemistry, Vol.no:67, Issue.no:3, pp.no:534–542, 2021.
2. Bharath Govindan, Muhammad Ashraf Sabri, Abdul Hai, Fawzi Banat, Mohammad Abu Haija, "A Review of Advanced Multifunctional Magnetic Nanostructures for Cancer Diagnosis and Therapy Integrated into an Artificial Intelligence Approach", Pharmaceutics, Vol.no:15, Issue no:3, pp.no:868, 2023.
3. "Giant Magnetoresistance Based Biosensors for Cancer Screening and Detection", Sensors / Biosensor Journal.
4. Hoshino K, Zhang X, et al. *Microchip-based immunomagnetic detection of circulating tumor cells (CTCs) using magnetic nanoparticle labeling and micro-fluidics, 2011.
5. Khazaei M "Nanosensors and their applications in early diagnosis of cancer", Science Direct, 2023.
6. "Recent Trends and Innovations in Bead-Based Biosensors for Cancer Detection", Sensors, Vol.no:24, Issue no: 9, 2024.
7. Ahn, E.C, "2D Materials for Spintronic Devices", 2D Materials and Applications, Vol.no:4, pp.no: 17, 2020.
8. Hu. G & Xiang, B, "Recent Advances in Two-Dimensional Spintronics", Nanoscale Res Letters, Vol.no15, pp.no: 226, 2020.
9. Feng, Y.P, "Prospects of spintronics based on 2D materials", WIREs Comput Mol Sciences, Vol.no:17, 2017.
10. Awschalom, D. D, "Quantum spintronics: engineering and manipulating atom-like spins in semi-conductors", Science, Vol.no:8, pp.no: 339, 2013.
11.Alizadeh N, Salimi A, Hallaj, "Magnetoimmuno-sensor for simultaneous electrochemical detection of carcino-embryonic antigen and α-fetoprotein using multi-functionalized Au Nanotags", Journal of Electroanal. Chem, Vol.no:811, pp.no:8-15,2018.
12. Guerrero S, Cadano D, Agui L, Barderas R, "Chemistry assisted antibodies immobilization for immune-sensing", Electroanal. Chem, Vol:837, pp.no:246–253, 2019.
13. Dadfar S.M, Roemhild K, Drude N.I, Von Stillfried S, "Iron oxide nanoparticles: Diagnostic, therapeutic and theranostic applications", Adv. Drug Deliv, Vo.no:138, pp.no:302–325. 2019.
14.Tian L, Qi J, Qian K, "An ultrasensitive electrochemical cytosensor based on the magnetic field assisted binanozymes synergistic catalysis of Fe3O4 nanozyme and reduced graphene oxide/molybdenum disulfide nanozyme", Sens. Actuators B Chem. Vol.no:260, pp.no: 76–684, 2018.
15. Yang J, Wang K, Xu H, Yan W, Jin Q, Cui D, "Detection platforms for point-of-care testing based on colorimetric, luminescent and magnetic assays: A review", Talanta, Vol.no:202,pp.no:96–110, 2019.
16. Xu Q, Liang K, Liu R.Y, Deng L, Zhang M, Shen L, Liu Y.N, "Highly sensitive fluorescent detection of p53 protein based on DNA", Nanoparticles, Vol.no:187, pp.no:142–147, 2018.
17. Hu Y, Li L, Guo L, "The sandwich type aptasensor based on gold nanoparticles/DNA/magnetic beads for detection of cancer

biomarker protein AGR2", Sens. Actuators B Chem. Vol.no:209, pp.no:846–852, 2015.
18. Park J.H, Saravanakumar G, Kim K, Kwon I.C, "Targeted delivery of low molecular drugs using chitosan and its derivatives", Adv. Drug Deliv. Rev, Vol.no:62, pp.no:28–41, 2010.
19. Kim D, Lee H, Kwon S, Hyun, Choi H, Park S, "Magnetic Nano-particles retrievable biodegradable hydrogel micro-robot", Sens. Actuators B Chem, Vol.no: 289, pp.no:65–77, 2019.
20.Roohi R, Emdad H, Jafarpur K, Mahmoudi, M.R, "Determination of Magnetic Nanoparticles Injection Characteristics for Optimal Hyperthermia Treatment of an Arbitrary Cancerous Cells Distribution", J. Test. Eval. Vol.no:48, 2020.
21. Alomari M, Jermy B.R, Ravinayagam V, Akhtar S, "Functionalized three-dimensional magnetic SBA-16 for treating breast cancer cells (MCF-7)", Artificial Cells Nanomed Biotech, Vol.no:47, pp.no:3079–3086, 2019.
22. Bucak S, Altan C.L, "Magnetic nanoparticles and cancer, Elsevier, Amsterdam, The Netherlands, pp. 105–137, 2016.
23. Hajba L, Guttman A, "The use of magnetic nanoparticles in cancer theranostics: Toward handheld diagnostic devices", Biotechnol. Adv. Vol.no:34, pp.no:354–361, 2016.
24. Chen Z, Wu C, Zhang Z, Wu W, Wang X, Yu, Z. "Synthesis, functionalization, and nanomedical applications of functional magnetic nanoparticles. Chin. Chem. Lett. Vol.no:29, pp.no:1601–1608,2018.