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RECENT DEVELOPMENTS IN TARGETED CANCER THERAPY AND PRECISION MEDICINE

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ABSTRACT

Background: Cancer treatment remains a critical area of clinical research, with numerous approaches developed depending on tumor type and stage. Recent advances in genetic and immunotherapy, bioinformatics, and genetic science have revolutionized cancer diagnosis and treatment. Emerging technologies such as gene delivery, oncolytic virotherapy, suicide gene therapy, and CRISPR/Cas9 offer promising therapeutic avenues.

Methods: This review provides a detailed analysis of the latest techniques of Gene therapy, artificial intelligence, Nanocarrier Delivery Systems, Immunotherapy, CAR T-Cell Therapy, Epigenetics, Vaccines, and Clinical translation and assessing their therapeutic potential in cancer treatment. A review of early critical studies focused on the integration of immunotherapy, nanotechnology, and artificial intelligence (AI) in cancer therapies with emphasis on targeted delivery systems and precision medicine.

KEYWORDS: Cancer, Oncolytic virotherapy, Nanomedicine.

1. INTRODUCTION

Targeted cancer therapy and precision medicine have transformed oncology from a generalized treatment paradigm into a molecularly guided discipline. Precision oncology uses genomic, transcriptomic, proteomic, and immunologic information to tailor therapies to individual patients and tumor characteristics. Recent advances in molecular diagnostics,

immunotherapy, gene editing, artificial intelligence (AI), and targeted drug delivery systems are accelerating this transition and improving clinical outcomes across multiple malignancies.

Evolution of Precision Oncology

Traditional chemotherapy acts broadly against rapidly dividing cells, often causing substantial toxicity. In contrast, targeted therapies selectively inhibit molecular pathways essential for tumor survival and progression. Precision medicine integrates:

- Next-generation sequencing (NGS)
- Whole-exome sequencing (WES)
- Liquid biopsy
- Biomarker-driven therapy selection
- AI-assisted treatment planning
- Molecular imaging and theranostics

These technologies enable clinicians to identify actionable mutations such as EGFR, ALK, HER2, BRAF, BRCA1/2, KRAS G12C, and MSI-H/MMRd signatures for individualized treatment strategies.

2. RECENT ADVANCES IN TARGETED CANCER THERAPY

Antibody–Drug Conjugates (ADCs)

ADCs have emerged as one of the fastest-growing areas in oncology therapeutics. These agents combine monoclonal antibodies with highly potent cytotoxic payloads, enabling selective delivery to tumor cells.

Recent ADC developments include:

- Datopotamab deruxtecan (Datroway)
- Trastuzumab deruxtecan
- Sacituzumab govitecan

These agents have shown major improvements in breast, ovarian, and lung cancers while reducing systemic toxicity compared with conventional chemotherapy. ADCs are increasingly being described as “guided missiles” against cancer because of their precision targeting capability.

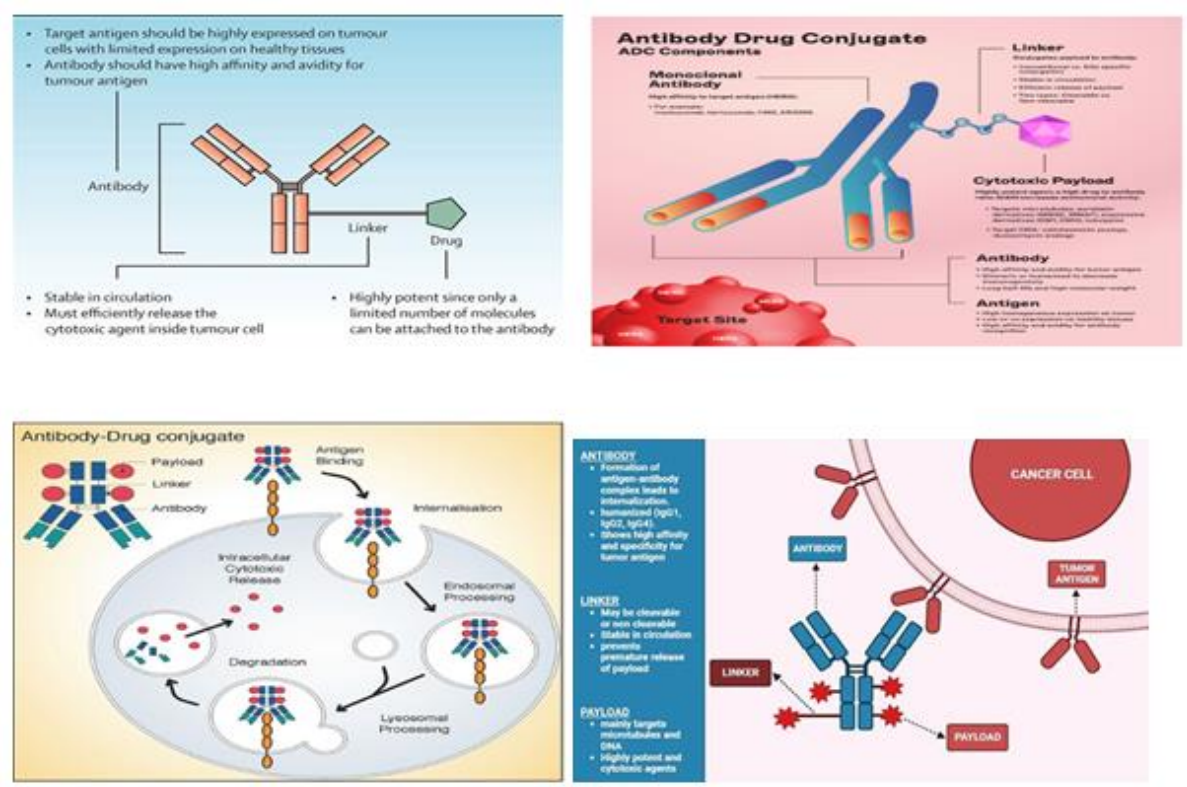


Fig: 1 Antibody–Drug Conjugates.

CAR T-Cell Therapy and Cellular Immunotherapy

Chimeric Antigen Receptor T-cell (CAR T) therapy represents a major breakthrough in hematologic malignancies.

Recent developments include:

- Expansion beyond leukemia and lymphoma
- Exploration in solid tumors
- In vivo CAR T engineering
- Multi-antigen targeting CARs
- Reduced manufacturing time

CAR T therapy has demonstrated remarkable remission rates in refractory blood cancers. However, challenges remain in solid tumors because of:

- Tumor heterogeneity
- Immunosuppressive microenvironment
- Antigen escape

Researchers are now engineering CAR T cells capable of secreting cytokines or localized therapeutic molecules directly within tumors.

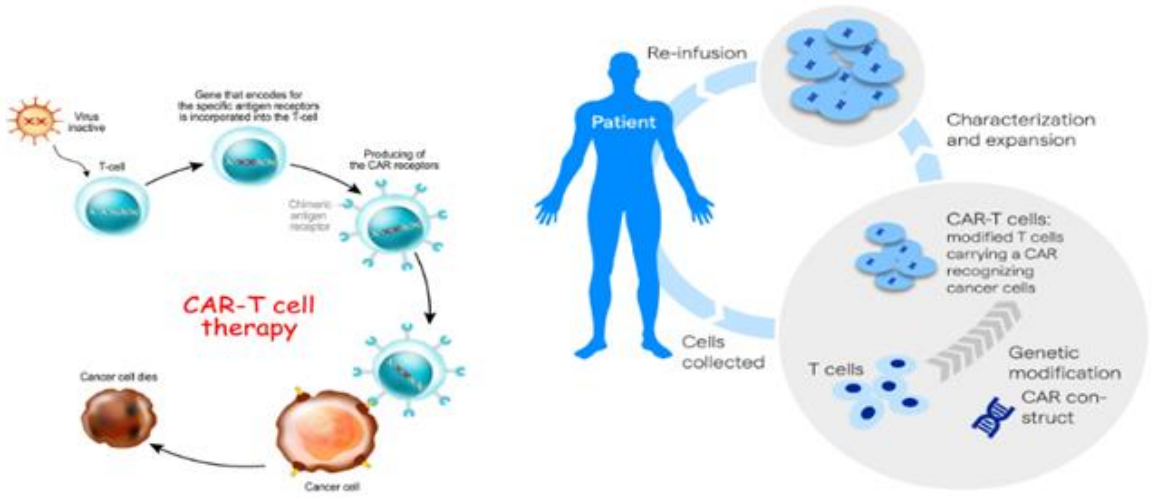


Fig: 2 CAR T-Cell Therapy.

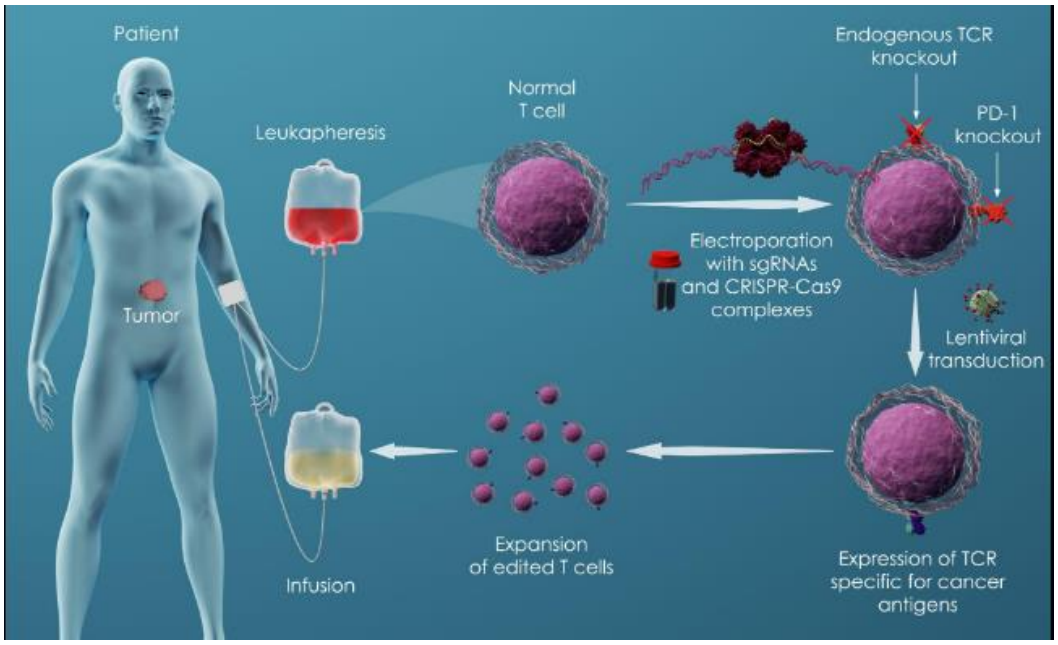


Fig: 3 Cellular Immunotherapy.

Gene Editing and CRISPR-Based Oncology

CRISPR-Cas systems are revolutionizing cancer therapy through:

- Precision oncogene disruption
- Tumor suppressor restoration
- Immune cell engineering
- Drug resistance reversal

Recent reviews highlight advancements in:

- Base editing

- Prime editing
- Multiplex genome editing
- Safer delivery vectors

Gene editing is also being used to improve immune-cell therapies by enhancing persistence and reducing exhaustion of engineered T cells.

Major limitations include

- Off-target effects
- Efficient delivery systems
- Long-term safety
- Tumor-specific editing

Nonetheless, CRISPR-based therapies are moving rapidly toward broader clinical translation.

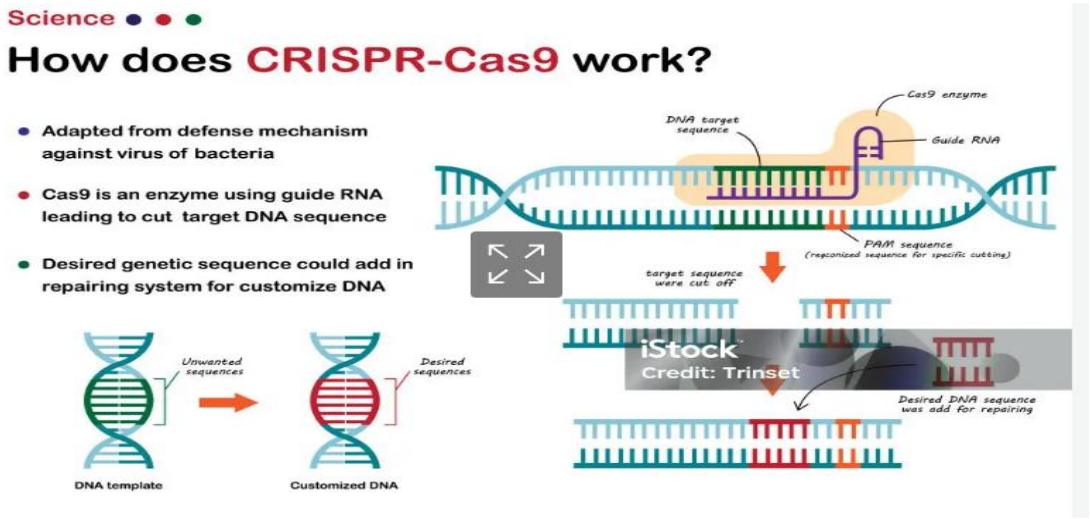


Fig: 4 CRISPR-Based Oncology.

3. LIQUID BIOPSY AND MOLECULAR DIAGNOSTICS:

Liquid biopsy has become a central tool in precision oncology. It detects circulating tumor DNA (ctDNA), exosomes, and circulating tumor cells from blood samples.

Recent advances include

- Early cancer detection
- Monitoring treatment response
- Detection of minimal residual disease (MRD)
- Real-time mutation tracking

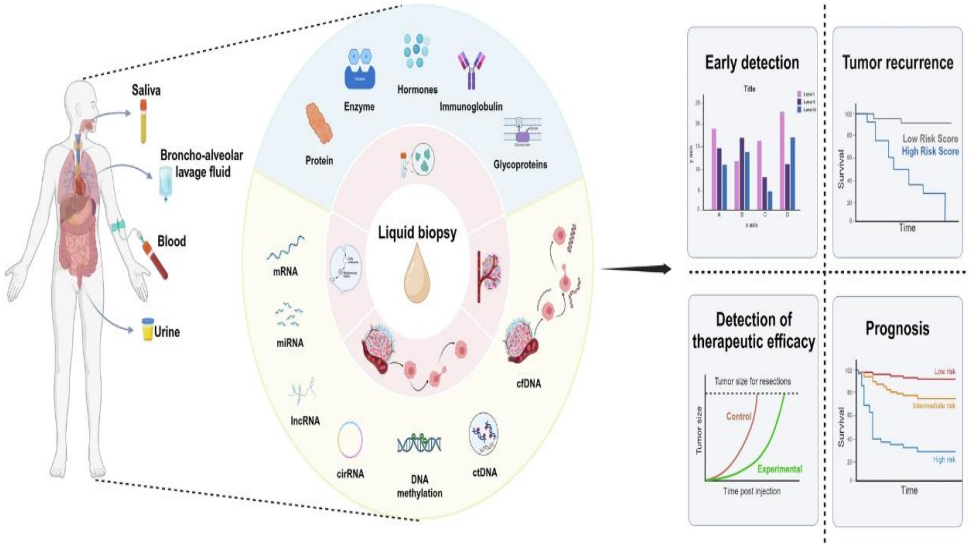
- Resistance mechanism identification

The NHS rollout of ctDNA-based testing for lung and breast cancer represents a landmark implementation of precision diagnostics at national scale.

Advantages over tissue biopsy include:

- Minimal invasiveness
- Faster turnaround
- Better representation of tumor heterogeneity
- Repeated longitudinal monitoring

Liquid biopsy is expected to become standard in monitoring metastatic and recurrent cancers.



Biology and detection of ctDNA

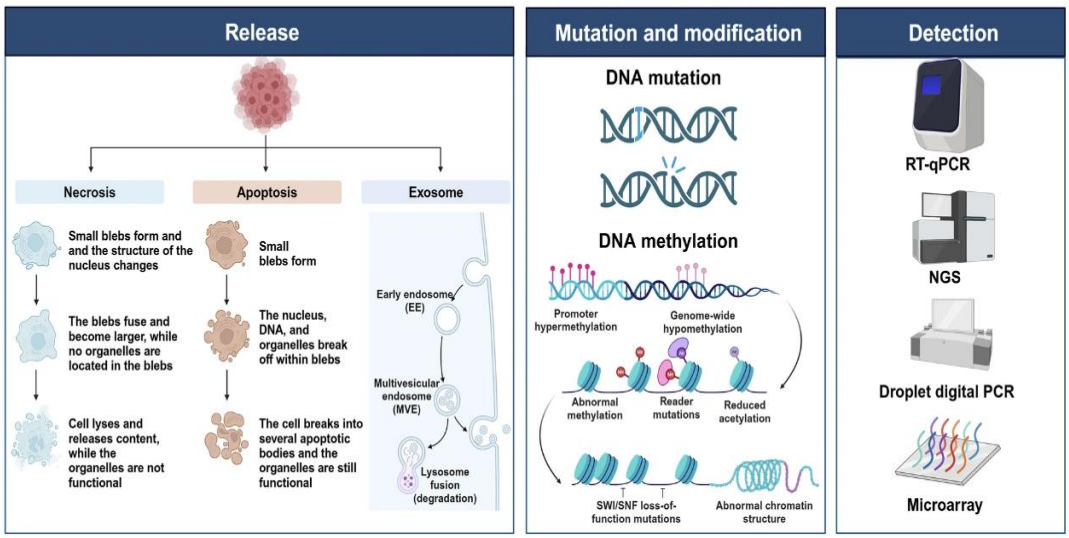


Fig: 4 Liquid Biopsy & Molecular Diagnostics.

4. PRECISION NANOMEDICINE AND TARGETED DRUG DELIVERY:

Nanotechnology is increasingly integrated into precision oncology to improve:

- Drug stability
- Tumor targeting
- Controlled release
- Reduced toxicity

Emerging nanoparticle systems include:

- Liposomes
- Polymeric nanoparticles
- Dendrimers
- Mesoporous silica nanoparticles

Recent studies demonstrate enhanced drug accumulation within tumor microenvironments while minimizing healthy tissue exposure.

Nanomedicine is also enabling:

- Co-delivery of drugs and immunomodulators
- Tumor microenvironment remodeling
- Stimuli-responsive drug release
- Combination immunotherapy platforms

These technologies may significantly improve treatment efficacy in difficult-to-treat solid tumors.

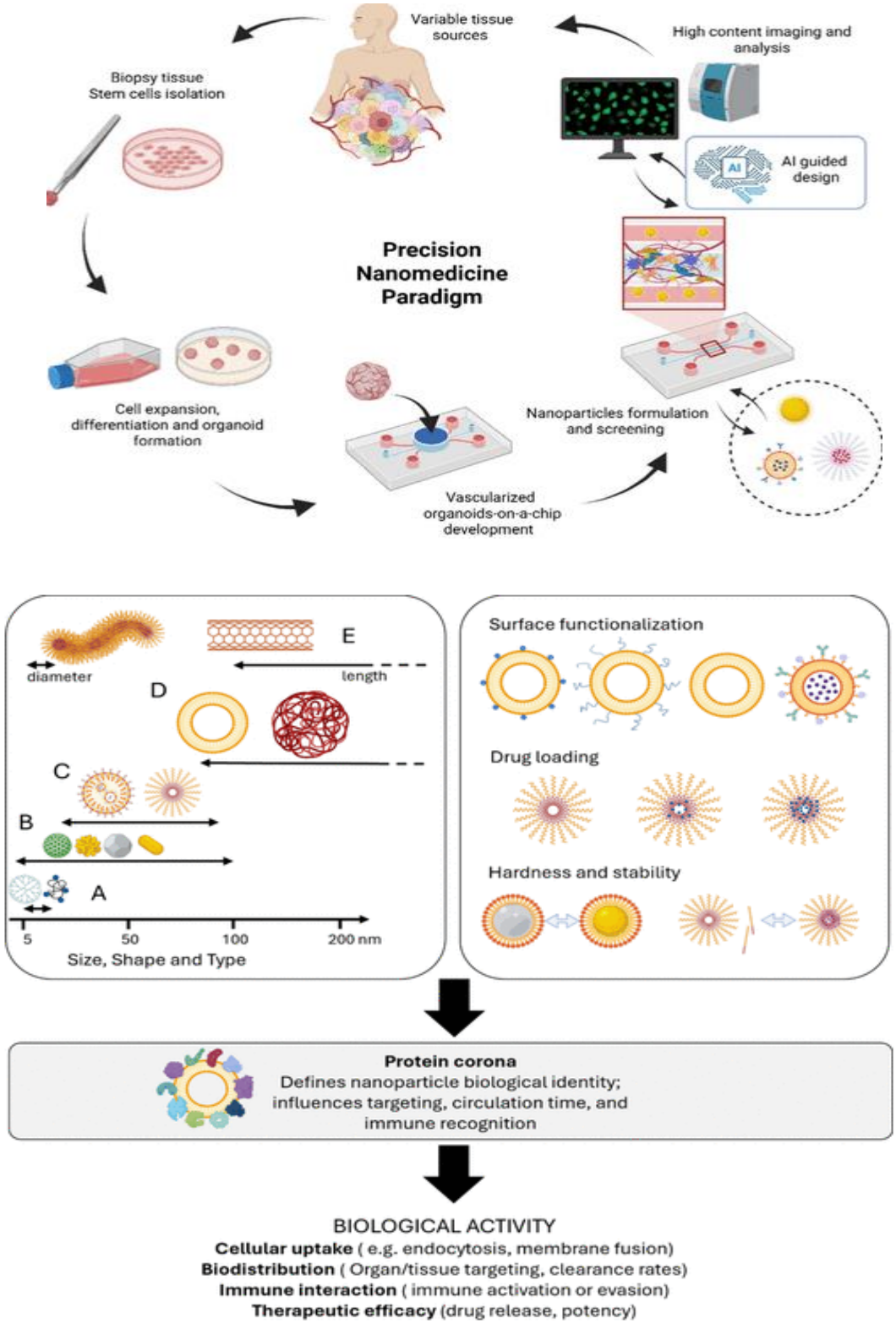


Fig: 5 Nanomedicine.

5. ARTIFICIAL INTELLIGENCE IN PRECISION ONCOLOGY

AI and machine learning are becoming integral to cancer diagnosis and treatment optimization.

Applications include

- Predictive biomarker discovery
- Radiomics and imaging analysis
- Drug response prediction
- Clinical decision support
- Multi-omics integration

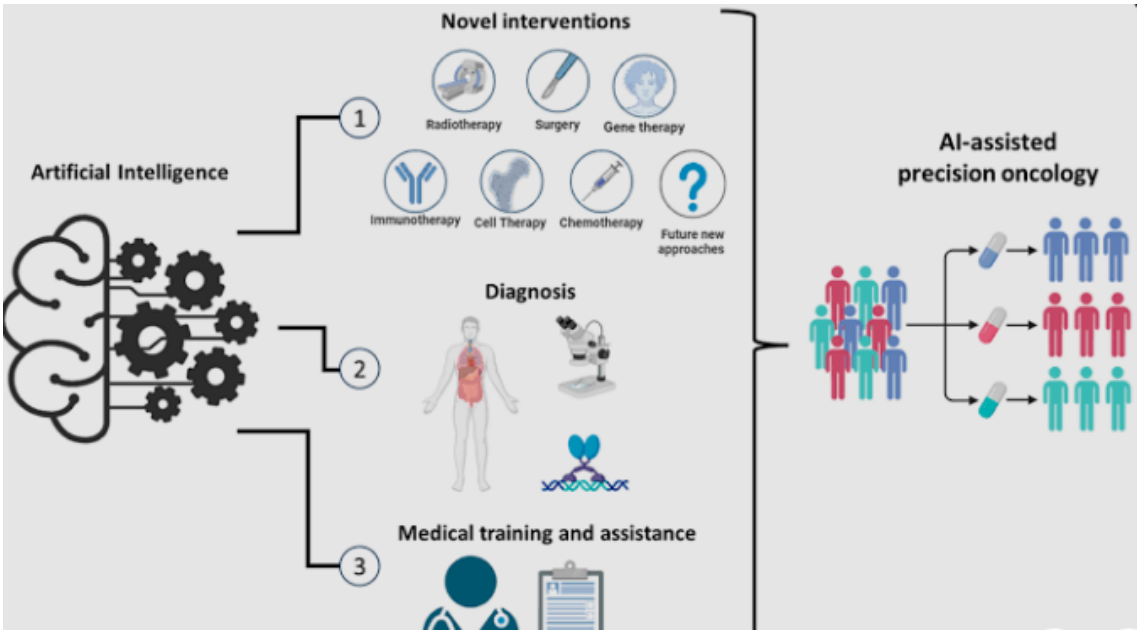
AI-driven precision oncology systems analyze genomic, imaging, and clinical data simultaneously to personalize treatment recommendations.

Radiology-based AI models are now being developed to predict targeted therapy response across multiple cancers using imaging features alone.

Challenges include

- Data standardization
- Bias in training datasets
- Regulatory oversight
- Interpretability of AI models

Despite these limitations, AI is expected to become foundational in precision cancer care.



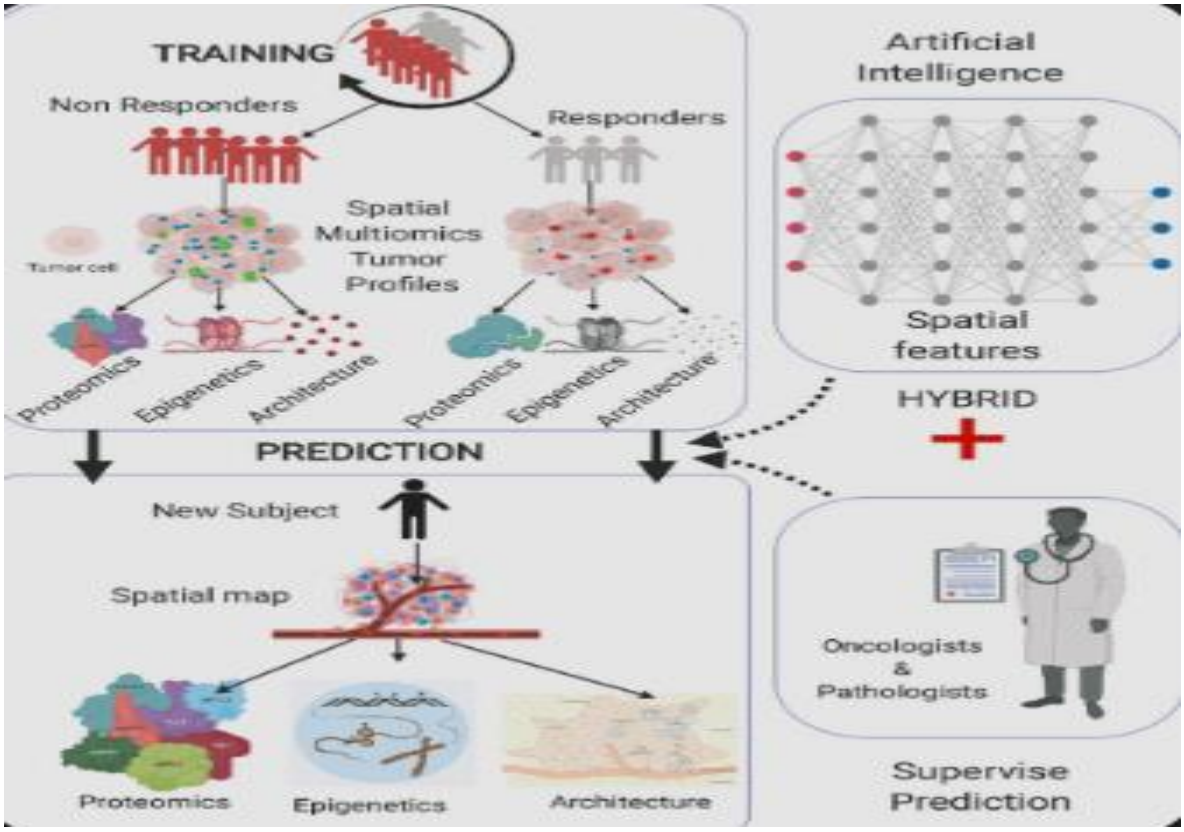


Fig: 6 AI & Machine Learning.

6. THERANOSTICS AND RADIOPHARMACEUTICAL PRECISION THERAPY:

Theranostics combines molecular imaging with targeted radionuclide therapy to simultaneously diagnose and treat tumors.

Recent innovations include:

- Lutetium-177 PSMA therapy
- Terbium-161 FAPI PTRT
- Fibroblast activation protein targeting
- Personalized radiodosimetry

These therapies enable highly localized radiation delivery to cancer cells while sparing healthy tissues.

Theranostics is showing promise in:

- Prostate cancer
- Neuroendocrine tumors
- Pancreatic cancer
- Sarcomas

This field is rapidly expanding within nuclear medicine and personalized oncology.

7. CHALLENGES IN PRECISION MEDICINE:

Despite substantial progress, several barriers remain:

Biological Challenges

- Tumor heterogeneity
- Drug resistance
- Clonal evolution
- Immune escape mechanisms

Technological Challenges

- High sequencing costs
- Data integration complexity
- Limited biomarker validation
- Insufficient longitudinal datasets

Clinical and Ethical Challenges

- Unequal access to advanced therapies
- Regulatory complexities
- Data privacy concerns
- Cost-effectiveness

CAR T-cell therapy and gene editing remain prohibitively expensive in many healthcare systems.

8. FUTURE DIRECTIONS

Future precision oncology is likely to focus on:

- Multi-omics integration
- AI-driven adaptive therapy
- Personalized cancer vaccines
- Real-time monitoring via liquid biopsy
- Combination immunotherapy
- In vivo gene editing
- Spatial transcriptomics
- Digital twins for oncology modeling

Longitudinal multimodal data analysis is emerging as a critical next-generation approach for dynamic treatment adaptation.

The convergence of AI, molecular biology, nanotechnology, and immunotherapy is expected to redefine cancer treatment over the next decade.

9. CONCLUSION

Targeted cancer therapy and precision medicine are fundamentally reshaping modern oncology. Advances in antibody–drug conjugates, CAR T-cell therapy, CRISPR gene editing, liquid biopsy, AI-assisted diagnostics, and nanomedicine are enabling more individualized and effective cancer care with fewer side effects. Although significant challenges remain regarding resistance, accessibility, and cost, ongoing innovations continue to move oncology toward truly personalized medicine. The future of cancer treatment will likely depend on integrated, data-driven, and biologically precise therapeutic strategies tailored to each patient's unique molecular profile.

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