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Integrating Modern Technologies in Oncology: Advances in Diagnostics, Therapeutics, and Research

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ABSTRACT :

Rapid technological progress from 2020–2025 has reshaped oncology across diagnostics, therapeutics and basic research. Key developments include improved immunotherapies (next-generation checkpoint inhibitors and engineered cell therapies), expanded liquid biopsy applications (ctDNA), single-cell and spatial transcriptomics to decode tumour heterogeneity, CRISPR and gene-editing strategies approaching clinical translation, nanoparticle-based targeted delivery systems, RNA-based vaccines and therapeutics, and widespread clinical/diagnostic use of artificial intelligence (AI). This review synthesises major advances during 2020–2025, highlights clinical and translational impacts, discusses remaining scientific and regulatory challenges, and proposes priority directions for future research and implementation.

Keywords: Immunotherapy; CAR-T; liquid biopsy; ctDNA; single-cell sequencing; CRISPR; nanoparticles; RNA cancer vaccines; artificial intelligence; precision oncology.

1. Introduction

Cancer research and clinical oncology have been transformed by convergent technological advances. Innovations in molecular profiling, cellular engineering, bioinformatics/AI, and drug-delivery platforms have shortened timelines from discovery to clinical application and enabled increasingly personalised care (Cancer Research Institute, 2025; Najafi et al., 2025).

2. Immunotherapy: checkpoint inhibitors, engineered cells, and vaccines

2.1 Immune checkpoint blockade and formulation advances

Immune checkpoint inhibitors (PD-1/PD-L1, CTLA-4) remain foundational across many tumour types. Recent efforts focus on rational combinations, predictive biomarkers of response, and more patient-friendly formulations (for example, subcutaneous formulations that simplify administration) (Desai, 2024).

2.2 CAR-T and next-generation engineered cell therapies

Chimeric antigen receptor T-cell (CAR-T) therapies have demonstrated clear success in haematologic malignancies and are being engineered to overcome the major barriers in solid tumours: antigen heterogeneity, immunosuppressive tumour microenvironment and poor trafficking. Next-generation strategies include multi-antigen targeting CARs, “armoured” CARs that secrete cytokines or checkpoint modulators, and allogeneic off-the-shelf products to improve scalability (Zugasti et al., 2025).

2.3 RNA-based vaccines and immunomodulators

mRNA vaccine platforms, validated by the COVID-19 response, are being repurposed for personalised neoantigen cancer vaccines and adjuvant immunotherapies. Early clinical data through 2024–2025 indicate robust immunogenicity; efficacy outcomes are under active investigation (Research reports, 2024).

3. Precision diagnostics: genomics, liquid biopsy, and single-cell technologies

3.1 Next-generation sequencing and precision matching

Comprehensive genomic profiling by next-generation sequencing (NGS) enables targeted therapy selection, detection of resistance mechanisms, and matching of patients to clinical trials. Improved standardisation of reports and integration into tumour boards have increased clinical utility (Parums, 2025).

3.2 Liquid biopsy (ctDNA) — monitoring, minimal residual disease, and early detection

Circulating tumour DNA (ctDNA) assays have advanced for non-invasive monitoring of treatment response, detection of minimal residual disease (MRD) and multi-cancer early detection (MCED). Commercial development has accelerated efforts to validate clinical utility across tumour types (Borea et al., 2025).

3.3 Single-cell and spatial omics

Single-cell RNA sequencing and spatial transcriptomics reveal intratumour heterogeneity, immune cell states, and niche interactions that underpin therapy resistance and metastatic behaviour. These technologies are increasingly incorporated into translational studies to discover biomarkers and rational combination therapies (Hawsawi et al., 2024).

4. Gene editing and nucleic-acid therapeutics

CRISPR and related gene-editing platforms have entered early oncology clinical trials, particularly for ex vivo engineered cell products where delivery and safety can be controlled. While the potential for in vivo editing remains compelling, obstacles include off-target activity, efficient delivery into solid tumours and immune responses to delivery vehicles (Cetin et al., 2025).

5. Nanoparticles and targeted drug delivery

Lipid nanoparticles, polymeric carriers and targeted conjugates improve tumour accumulation of chemotherapeutics, oligonucleotides and mRNA payloads. By improving pharmacokinetics and enabling combination payloads (for example drug + immunomodulator), nanocarriers reduce systemic toxicities and widen therapeutic windows (Rahman et al., 2025).

6. Artificial Intelligence and computational oncology

Artificial intelligence and machine learning methods are rapidly integrated into imaging (radiology, pathology), prognostic modelling, clinical decision support and drug discovery. Key barriers include dataset bias, interpretability of models, regulatory pathways for clinical deployment and integration with electronic health records. Federated learning and synthetic data generation are potential strategies to enlarge training datasets while protecting privacy (Najafi et al., 2025).

7. Translational successes and selected recent milestones

Selected translational milestones exemplify acceleration from discovery to practice:

- Expansion of CAR-T approvals in haematologic malignancies and multiple active trials addressing solid tumours (Zugasti et al., 2025).
- Commercial momentum for multi-cancer blood tests and ctDNA-based MRD monitoring (Borea et al., 2025).
- Early CRISPR-based oncology trials demonstrating feasibility of ex vivo editing strategies (Cetin et al., 2025).

(Figure 1: timeline of selected milestones — see Figure 1, JPG).

8. Challenges, limitations, and ethical/regulatory issues

Key challenges persist:

- Clinical validation: numerous biomarkers and platforms require prospective, randomised clinical validation to establish clinical utility (Parums, 2025).
- Equity and access: sophisticated testing and therapies are resource-intensive and risk widening disparities in care.

- Data governance: robust frameworks are required for large AI models trained on multi-institutional data while preserving patient privacy.
- Biological hurdles: effectively targeting heterogeneous solid tumours, delivering gene editors in vivo, and managing immune adverse events remain priorities.

9. Future directions and research priorities

Priority areas for research and translation include:

1. Prospective trials that use ctDNA MRD to guide adaptive therapy strategies (Borea et al., 2025).
2. Improved delivery systems for in vivo CRISPR and RNA therapeutics to enable safe targeting of solid tumours (Cetin et al., 2025; Rahman et al., 2025).
3. Standardised, prospective validation frameworks for AI tools in oncology integrating multi-institutional datasets (Najafi et al., 2025).
4. Incorporation of single-cell and spatial omics into clinical trial designs to stratify patients by microenvironmental features (Hawsawi et al., 2024).

10. Conclusion

Modern technologies — including refined immunotherapies, liquid biopsy, single-cell genomics, gene editing, nanoparticle delivery systems, and AI — are converging to enable more precise, adaptable cancer care. Realising their full potential requires rigorous clinical trials, solutions to ensure equitable access, and careful regulatory and ethical oversight.

Figures

- **Figure 1.** Timeline of selected oncology technology milestones (2020–2025). See downloaded JPG: *figure1_timeline.jpg*.
- **Figure 2.** Multi-modal precision oncology pipeline: tumour biopsy, liquid biopsy, single-cell/spatial omics, AI analytics → therapy selection. See downloaded JPG: *figure2_pipeline.jpg*.
- **Figure 3.** Summary table: technologies, clinical status, and key advantages. See downloaded JPG: *figure3_table.jpg*.

(Place each figure in the manuscript near its first citation. For Harvard style captions, ensure figure number and concise caption appear beneath each figure.)

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