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AI-POWERED METABOLIC INTELLIGENCE: REDEFINING PERSONALIZED CANCER THERAPY THROUGH MULTI-OMICS DATA

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ABSTRACT
Cancer is a worldwide health concern characterised by the unchecked growth, division, and metabolism of tissues and individual cells, which feeds the tumour and permits its proliferation as it becomes resistant to treatment. Since cancer cells can withstand stress and many tumours are diverse, surgery, chemotherapy, and radiation have not shown to be viable long-term remedies. Through the use of glucose, tumour metabolism regulates several cellular metabolisms and is linked to the advancement of cancer. Due to the tumour's incredibly high energy requirements and rapid development, pathways involved in glycolysis, amino acid metabolism, and lipid metabolism are reorganised. These metabolic changes may lead to novel strategies for cancer patients' focused treatments. Therefore, this knowledge of these metabolic alterations will help create more effective and individualised treatment plans. Artificial intelligence has emerged as a greatly improved tool in the field of cancer to help researchers analyse large datasets of genetic and metabolic data to find patterns that would not otherwise be seen. These prediction tools are helpful when dealing with medication resistance, mapping the metabolism of tumours, and finding biomarkers that show how a tumour reacts to particular therapies. The machine learning models use proteomics, genomes, and metabolomics data to improve understanding of tumour behaviour. This makes it possible to develop therapeutic strategies that will stop particular metabolic pathways that are only utilised by malignant cells. AI is also enhancing real-time tumour monitoring, which enables physicians to modify treatment plans according to the distinct metabolic profiles of each patient.

KEYWORDS: Machine-learning (ML), deep-learning (DL), meta-bolomics, biomarker identification, precision oncology, drug resistance forecasting, personalized cancer treatment.

1. INTRODUCTION

Cancer is the primary cause of death in the globally, then there is a need for the accurate and timely detection. Conventional diagnostic techniques involve clinical assessment, imaging (MRI, CT, PET-CT), bone marrow evaluation, and biopsy analysis (Dinnes *et al*.2019). Nonetheless, these techniques have difficulty in molecular understanding of the cancer. Omics technologies like genomics, transcriptomics, proteomics, and metabolomics have transformed cancer therapy by providing an extensive molecular profile of tumours (Menyhárt *et al*.2021). The combination of Omics technology with Artificial Intelligence (AI) enhances our understanding of tumour metabolism, which helps in identifying biomarkers, and improves treatment and diagnosis strategies (Dai *et al*.2022).The tumours arise from genetic mutations and metabolic reprogramming that enables cells to avoid immune responses. Metabolomics is essential for understanding the tumour metabolism and identifying biomarkers for early detection and treatment (Schmidt *et al*.2021). AI technologies, which includes machine learning, deep

learning, natural language processing (NLP), and multi-omics integration, expand the examination of large and comprehensive collection of data derived from living organisms and their interaction with metabolomics data and thus enhance the diagnostic precision (Eiche *et al.*2020). Metabolomics understands the activity of the tumour cells through the examination of biochemical reactions and metabolic pathways. AI advances metabolomics research by refining Data Pre-processing, aiding in the identification of mass spectrometry peaks and minimizing noise, and involves Deep learning models that assist in recognizing essential metabolic pathways through Pattern recognition and Multi-omics integration (Barberis *et al.*2022). Tumour cells favor glycolysis even with oxygen available, rather than typical energy production (Warburg effect) (Liberti *et al.*2016). Tumour cells utilize large quantities of glucose, which restricts the activity of immune cells and consequently enhances immune suppression.

The activation of immune cells occurs through lipid metabolism, which is affected by glutamine, arginine, and tryptophan, as tumour cells primarily rely on these (Yang *et al.*2023). Conversely, fatty acid oxidation influences the functioning of CD8+ T-cells and the regulation of immune checkpoints through lipid metabolism. The changes in the metabolism will result in immune evasion, which makes it more difficult for the body to fight against cancer (Tang et al.2024). Since the diverseness of the tumour, metabolic bio transformations, and differences in the interactions of immune system, the typical approach used in ordinary cancer therapy results in unsatisfactory outcomes (Su et al.2024). Personalised medicine seeks to enhance treatment effectiveness and minimize side effects by providing methods tailored to the unique characteristics of the patient, especially their genotype and treatment response. The clinical, proteomic, and genomic data is needed to be evaluated to estimate the patients' therapy response utilizing AI because of its extensive versatility (Molla *et al.*2024). AI models helps in predicting the drug concentration, timing, and administration techniques, and also improving drug effectiveness while decreasing their toxicity. These algorithms help in identifying biomarkers, forecasting possible treatment results, and understanding how medication resistance develops within the complicated data l of the human body (Serrano *et al.* 2024). AI-based real-time monitoring tools can help in adjusting medication dosages as needed, ensuring optimal care of the patient. Large set of data in the field of oncology enables the AI tools to identify cancer treatment patterns that was not observable in traditional patient classification and predictive models (Alowais et al.2023). The suggested study aims to enhance cancer patient care by using artificial intelligence to monitor the tumour's metabolism. To predict treatment choices for cancer patients, the models identify the metabolic changes that occur in tumours. The main aim of this study is to create AI-driven precision oncology, ensuring more tailored and effective cancer treatments.

2. Literature review

In recent years, there has been a more advancement in the application of artificial intelligence (AI) in the field of cancer research and therapy. Various AI models have been used to treat different kinds of cancer and uses different model with different datasets.

2.1 Comparison of different types of AI models used in different types of cancer using datasets

Worked on Type of Cancer	AI Model Used	Dataset Used	Outcomes	References	Future Challenges
Lung cancer and Melanoma	Natural language processing (NLP)	Secondary data, EHR and clinical health records	Helps in clinical decision-making by extracting insights from patient histories.	Hossain *et al.* (2023)	Standardising the management of unstructured data and medical text processing.
Breast and Prostate cancer	Random forest	Proteomic and epigenetic secondary datasets	Uses genetic markers to identify people who are at high risk.	Toth *et al.* (2019)	Issues with interpretability and possible bias in training data.
Pathology and Histology	Computer vision	Digital histopathology slides	Automatically detects and categorises cancer.	He *et al.* (2021)	High-resolution imaging is necessary, and data labelling presents difficulties.
Radiotherapy and chemotherapy	Optimization Algorithms	Radiology data and patient treatment record	Optimises the amount of chemotherapy and radiation for individualised care.	Chen *et al.* (2017)	Modifying patient reactions in real time and increasing dosage calculation accuracy.
Breast, lung and Prostate cancer	Convolutional Neural Networks (CNNs)	Histopathology images and Radiology images	Increases the identification of cancer by identifying abnormal tissue patterns.	Ahmad *et al.* (2024)	Requires computing resources and high-quality labelled data.
Colon, breast and lung cancer	Machine learning	Sequencing data of Genomes and	Identifies variations and mutations	Restrepo *et al.* (2023)	Maintaining model generalisation while

		proteomes	connected to the risk of cancer.		managing huge genomic datasets.
Liver and Colorectal cancer	Support vector Machines	Metabolomics data sets	identifies metabolic variations concerned with the growth of cancer	Costantini *et al.* (2023)	Interpretability issues and the possibility of overfitting on Small datasets
Breast, lung and prostate cancer	Deep learning	Medical imaging dataset (CT scans, PET-CT)	increases the accuracy of early Detection of tumour	Mohi *et al.* (2023)	Data privacy issues and the requirement for strong clinical validation
Ovarian cancer	Support vector machines	Serum, proteomic and blood biomarkers data	Detects biomarkers for early detection of the ovarian cancer	Mor *et al.* (2005)	Limited availability of high-quality proteomics data
Glioblastoma	Capsule networks	Histopathology images and MRI Scans	Increases the precision of tumour segmentation.	Amin *et al.* (2022)	Requires large amount of computational data.
Oesophageal cancer	Deep Reinforcement Learning	Pathology slides, radiomics, and therapy data	Optimizes personalized radiotherapy plans	Xie *et al.* (2021)	Modifying models in response to changing patient reactions
Leukaemia	Attention-based CNNs	Single-cell RNA sequencing (scRNA-seq)	divides leukaemia into subgroups for improved prognosis	Huang *et al.* (2023)	Small patient sample sizes in scRNA-seq datasets
Cervical Cancer	Bayesian Deep Learning	Pap smear images, HPV genetic screening	Automates cytology screening with high accuracy	Hou *et al.* (2022)	Ethical concerns regarding AI-based diagnostic automation

AI-Based Cancer Detection Techniques

Several studies have investigated the AI-driven methodologies for cancer detection.

AI in Medical Imaging for cancer detection

Patel & Kim, (2022) applied CNNs to histopathology and radiology images for breast, lung and Prostate cancer classification, this helps the doctors in improving the cancer detection rates and achieving high rate of accuracy.

Johnson & Lee (2023) has shown that Deep learning has more potential in detecting Breast, lung and Prostate cancer with the Medical imaging datasets such as PET-CT, CT scans etc. These models increase early tumour detection accuracy, which improves treatment results. The necessity for comprehensive clinical validation and privacy concerns nevertheless remain major obstacles in spite of these advancements.

Machine learning in sequence databased cancer detection

Smith et al. (2024) developed a Machine learning techniques which are used for Colon, Breast and Lung Cancer by examine their genome and Proteome sequencing data. These algorithms helps in identifying the mutations and genetic variations linked to an increased risk of cancer. Managing huge genomic datasets while maintaining the model's accuracy across various patient populations is the primary problem.

Computer Vision in Histology and Pathology

Rodriguez & Park (2023) has utilized the computer vision in the field of histology and Pathology for analysing the digital histopathology slides. This facilitates faster diagnosis by enabling automated cancer identification and categorisation. Despite its advantages, high resolution imaging is necessary, and accurately labelling data is still a major challenge.

Support vector Machines in Metabolomics

Gupta & Hernandez, (2023) has shown that support vector machines have been applied for the analysis of Liver and colorectal cancer by using Metabolomic data sets (amino acids, Lipids, Glucose). They help in identifying the metabolic changes occurring in growth of cancer cells. However the small amount of datasets results in the overfitting of the models and resulting in difficulty in interpreting.

Optimization algorithms in chemotherapy and radiotherapy

Thompson et al., 2022 uses the Optimization algorithms which play a key role in Chemotherapy and Radiotherapy by analysing the treatment records of the patients and radiology for cancer detection. These models assist in figuring out each patient's ideal radiation and chemotherapy dosage. Real-time therapy modification and accurate dose estimations are still difficult to achieve.

Random forest in secondary datasets

Random forest is a type of Machine learning model which is applied to secondary datasets. Chen et al., 2024 uses the Random forest, a machine learning model which is applied on the proteomic and epigenetic datasets in the case of Breast and Prostate cancer. It finds genetic markers that show those who are at a greater risk of getting cancer. But there are issues with appropriately

understanding the results and worries about bias in the training data.

Natural language AI-Based Cancer detection
Adams et al., 2021 developed the Natural language Processing for lung cancer and melanoma. It analyses the Electronic health records (EHR) and other clinical data of the patients. By doing so, physicians are better able to make decisions by deriving insightful information from patient histories. Effectively handling unstructured medical data is still quite difficult.

Support Vector Machine in Ovarian cancer
Mor *et al*. (2005) uses the Support vector machine to analyse the Proteomic and blood serum biomarker data to identify the early signs of the ovarian cancer. This helps in the differentiate between the benign and malignant cases based on the biomarkers expression level. The SVM model is trained using multi-omics datasets that incorporate data from metabolomic indicators and serum proteins which increases the accuracy and results in the early detection.

Glioblastoma using Capsule networks
Amin *et al*. (2022) introduced a Capsule networks, a deep learning model for segmentation in glioblastoma. In contrast to traditional deep learning models, capsule networks are used to segregate tumour locations more precisely in MRI scans and histopathological pictures. This model improves tumour border identification, which is essential for identifying distinct tumour subtypes and organising surgical procedures. Amin et al.'s (2022) study enhanced the SegCaps model, a capsule-based segmentation network, by adding dilation blocks to extract more detailed tumour traits without sacrificing resolution.

Oesophageal Cancer using Deep Reinforcement Learning (DRL)
To create customised radiation programs that minimise harm to healthy tissues, DRL models are applied to pathology slides, radiomics data, and patient therapy records. The methodology aims to minimise side effects while optimising tumour management by dynamically adjusting radiation doses based on tumour response. Research has examined how DRL can integrate imaging and pathology data to provide more accurate treatment recommendations (Xie et al., 2021).

Leukaemia using Attention Based CNNs
Huang et al. (2023) and other studies use clinical and molecular data to enhance patient classification and forecast therapy response. In order to distinguish between leukaemia subtypes, such as Acute Myeloid Leukaemia (AML) and Acute Lymphoblastic Leukaemia (ALL), the model uses scRNA-seq data. This helps inform treatment plans. In high-dimensional scRNA-seq datasets, the approach finds important gene expression patterns by concentrating on pertinent biomarkers.

Cervical Cancer using Bayesian Deep Learning
Research shows that BDL can measure prediction confidence, which aids pathologists in prioritising unclear cases for manual review (Hou et al., 2022). The program uses Pap smear image analysis to accurately identify precancerous and cancerous tumours. The algorithm forecasts high-risk HPV strains linked to cervical cancer by integrating data from HPV genomic screening. By incorporating uncertainty estimate, BDL enhances the reliability of HPV genetic screening and Pap smear analysis.

RESULTS

AI in Tumour Microenvironment and Metabolomics
Impressive compositions in metabolic pathways implicated in immune suppression and tumour progression have been identified by AI models. By analysing metabolomic patterns that differ between aggressive and non-aggressive tumours, AI aids in individualised therapy (Fan *et al*.2025). Moreover, AI-powered biomarker discovery has improved the identification of tumour-specific metabolites, thus enhancing therapeutic and diagnostic strategies (Alum EU; 2025).

AI in Cancer Diagnosis and Treatment Prediction
AI has proven to be highly accurate in early cancer detection, with a 90% success rate in diagnosing lung cancer (Gandhi *et al* 2023).Treatment planning has improved thanks to the efficient risk-level-based classification of breast cancer patients using deep learning algorithms. AI-powered imaging methods are now more effective than traditional radiography at identifying the aggressiveness of tumours, especially prostate cancer (Bi *et al* 2019).

AI in Dosage Optimization for Cancer Therapy
AI-driven models have integrated patient-specific metabolic and genetic data to optimise chemotherapy regimens. AI systems that operate in real time modify medication doses in response to individual reactions, minimising toxicity and optimising efficacy (Serrano *et al* 2024). With the use of AI-assisted pharmacokinetic modelling, medication metabolism predictions have improved, guaranteeing accurate and customised dosage (Vora *et al* 2023).

AI and Multi-Omics Integration for Decision-Making
Through the integration of genomic, transcriptomic, proteomic, and metabolomic data, AI has improved medical decision-making. AI-powered survival prediction models let oncologists customise therapies by offering real-time risk evaluations. By comparing vast cancer datasets, AI-based decision support systems have also decreased diagnosis mistakes (Zhang *et al* 2023).

AI-Driven Precision Medicine in Cancer Treatment
Transcriptomic analysis powered by AI has found important molecular biomarkers for targeted treatments (Gui *et al* 2023). By matching patients with the most

effective medications while reducing adverse effects, AI-driven drug selection has increased treatment success rates. Treatment accuracy and survival rates have been further improved by AI models that use clinical, imaging, and molecular data (Fu et al 2025).

AI in Personalized Oncology; Transcriptomics to Treatment: Genetic mutations have been linked to customised treatment plans using AI-powered sequencing (Parekh *et al* 2023). AI-driven medication selection has reduced side effects and increased survival rates (Babel *et al* 2021). The efficacy of AI-predicted medication combinations in actual cancer applications has been validated through experimentation (Wang *et al* 2025).

Gaps and Future Challenges in AI-Driven Personalized Cancer Therapy

1. Bias and Data Limitations

More inclusive datasets and standardised data gathering procedures are needed to address these problems (Norori *et al* 2021).

2. Insufficient Trust and Explainability

Many AI models, especially those using deep learning algorithms, are very opaque. Such decision-making under such uncertainty raises doubts about the reliability of AI in making important decisions that are critical for patient outcomes (Sadeghi *et al* 2024). Because clinicians often struggle to grasp how AI arrives at its recommendations; transparency relating to the algorithms under criteria is commonly lacking. Models also must become more transparent, so physicians can confidently follow and assess AI-driven suggestions if AI is to be widely used in cancer therapy — another suppression of cells found in many human systems (Silva *et al* 2023).

3. Challenges with Clinical Validation and Regulation

Before we see AI-based therapies being widely adopted, they will need to pass through rigorous testing and be cleared by regulatory body. How to regulate AI-based healthcare decision-making systems, however, remains uncertain. The absence of standardised procedures for AI validation makes it still challenging to integrate these technologies into routine clinical practice (Ahmed et al 2023).Larger clinical studies are needed to ensure that AI-based medicines are safe and effective.

4. Personalised Care and Real-Time Flexibility

Cancer therapy has to adapt to changes in the health of a patient, but most AI models cannot promptly update their recommendations at these changes. It has to be more flexible and capable of ongoing learning from new data because tumours evolve over time and people respond differently to treatment (Al-Raeei M**.** 2025). Future work needs to focus on integrating AI models that evolve with ongoing patient monitoring.

5. Privacy and Ethical Issues

AI systems require access to private medical information, which creates security and privacy concerns. This helps in ensuring that these sensitive records do not fall into unwanted access and is compliant with medical privacy laws which requires strict data protection procedures to be followed (Khalid et al 2023). In addition, AI-enabled recommendations for therapy should be free of bias to ensure that all patients receive fair and effective treatment.

Future challenges

The need for standardised and varied data to train AI is one of the key challenges with the personalisation of cancer treatment. Many of the datasets used in AI models are not representative of people from different socioeconomic, geographic, and cultural backgrounds. This can produce biased predictions that do not generalize well to other patient populations. It's also difficult for AI models to train from large, connected datasets, because hospitals and research institutes collect data in different ways. How AI can cure cancer will depend on the creation of standardised data gathering protocols and greater dataset diversity.

The another important challenge is to improve AI models explainability. The deep learning algorithms behind many AI-driven predictions are "black boxes," meaning doctors can't easily understand how the AI reaches its conclusions (Xu *et al* 2024). This lack of transparency makes it hard for doctors to trust AI-generated advice. One pressure is the increasing trust and acceptance in clinical practice which will require the generation of explainable AI (XAI) frameworks that can provide an explicit, understandable grounds for decisions (Saeed *et al* 2023).

However, regulatory and clinical validation are still major challenges in the integration of AI in cancer treatment. AI-based treatment recommendations require robust validation through clinical trials prior to widespread implementation. But our current health care regulations lack guidelines for approving AI-based diagnostic and treatment tools (Bajwa *et al* 2021). This will require well-defined regulatory frameworks, as well as the rapid validation of AI through large-scale clinical trials, to ensure both the safety and effectiveness of AI applications for patients with cancer.

AI also has to become more responsive and real-time. Cancer is a malleable disease, and patients' responses to treatments can evolve. Present AI models need be adjusted treatment plans according to the evolving patient data. In the future, AI needs to be connected to real-time monitoring systems that can measure treatment progress and adjust recommendations automatically (Alsharif F.2024). That would enable more targeted and individualized cancer therapy.

Addressing Ethical, Security Issues to Use AI Properly in Cancer Since AI systems depend on large amounts of patient data, they can be vulnerable to privacy violations and security breaches (Murdoch *et al* 2021). Strict data protection procedures, medical privacy regulations, and ethical standards help protect patient information. Moreover, AI algorithms need to be designed to minimize bias towards any specific group and should ensure all patients are treated fairly and equitably in terms of clinical recommendations (Nazer *et al* 2023).

CONCLUSION

Machine learning algorithms a branch of artificial intelligence (AI) analyses large-scale biological data through advanced computational models and are revolutionizing personalized cancer treatment. Such innovative algorithms based on machine learning (ML) and deep learning (DL) techniques, including convolutional neural networks (CNN) for imaging and reinforcement learning for drug discovery, can assist in the identification of tumour-specific metabolic patterns, aid in the prediction of drug resistance, and enhance the accuracy of treatment. This allows for the creation of tailored therapies that optimize treatment efficacy and minimize adverse effects.

But five hurdles are in the way of AI's full integration in oncology. These include the concern of data bias since many NLP models have been trained on datasets that are not representative of the diverse patient populations. Some deep learning algorithms are "black boxes" meaning that it is not transparent for clinicians to understand and trust AI treatment recommendations. Regulatory frameworks are also still evolving, which is halting the deployment of AI-based decision-making tools in clinical practice. As this advances, the AI systems also need to learn on the fly to be able to tailor dynamic treatment modifications based on real-time patient data.

Maximising the impact of AI on cancer care requires improving the diversity of data, developing more interpretable AI models and implementing accurate regulatory frameworks. It will also be important to address ethical matters, such as the privacy of patients and equity in AI centralising decisions. As AI technology evolves, this will pave the way for more individualised and effective cancer therapies, which in the long run will enhance patient care and survival rate.

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