Mini Review
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AI-driven precision and personalization in CAR-T therapy

Volume 13 Issue 1 - 2025

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Received: December 30, 2024 | **Published:** January 16, 2025

Introduction

Artificial intelligence (AI) is playing a larger role in CAR-T cell therapy, contributing to different stages of the pipeline regarding patient selection, in-vivo activity, and post CAR-T cell treatment monitoring. Much of the work is centered around the use of AI in patient follow-up, particularly in being able to predict adverse effects including cytokine release syndrome (CRS) and sepsis after therapy. Instrumented wearable systems are built to keep track of physiological parameters so that quick changes can be remotely monitored and acted upon.[1–3]

During the selection of the patient, biomarker analysis driven by AI is essential to choose the right patients, which improves therapeutic effectiveness, resulting from an optimized CAR-T cell selection. During the preparatory stages, selection and timing of healthy CD3-T cell extraction—proposed to maximize therapeutic impact—is aided by AI algorithms to refine accuracy.[4,5] In addition, some examples of predictive assessments during genetic engineering and expansion of cells predict the quality and clinical activity of the final cell product. Moreover, advanced AI-driven sensors and spectrometry tools maximize the monitoring of cell culture that improve the control of cell growth and viability.[6]

Real-time and personalized process control and production scheduling are necessary to scale up CAR-T cell manufacturing, and this becomes the responsibility of AI. Relevant to this context, the AIDPATH project has been implementing digital twins to bioreactors for CAR-T cell expansion based on nutrient consumption and metabolite production that can allude timely predictions of cell expansion completion to achieve cell dose targets (UC1).[7]A second system uses "soft sensors," which build upon available bioreactor sensors to combine multiple sensor inputs into real-time notifications (UC2).[8,9] Scheduling algorithms (UC3) are able to align parallel manufacturing cycles across different patients to cope with these uncertainties through the cell-expansion process time and the time they will be ready to treat the patients.[10]

Progress will include dynamic control of bioreactor parameters based upon individual patient needs to enable highly individualized CAR-T cell therapies. In the context in which personalized patient-centered therapies are paramount, AI-powered clinical decision support systems (UC5) assist in matching the CAR-T cell characteristics and complementary therapies to individual patients in accordance to their profiles by establishing a balance between efficacious therapeutic effect and safety.[11,12]

These advancements in AI-driven personalization do not end with the manufacturing and preparatory stages. AI is also proving crucial for monitoring and adjusting CAR-T therapy post-administration. Following infusion, the therapeutic journey of CAR-T cells within a patient is highly individualized, involving complex interactions with the host's immune system. AI-enabled systems monitor patients for any early signs of potential complications, such as cytokine release syndrome (CRS) and neurotoxicity, which are common adverse effects associated with CAR-T therapy.[13] Real-time data analysis, derived from patient biomarkers and physiological indicators, provides predictive alerts to healthcare teams, enabling rapid responses that can mitigate the severity of these complications. This is especially beneficial for managing cases remotely, where AI-driven wearables and monitoring devices continuously track patient health indicators, thus ensuring prompt intervention when necessary.[14]

In addition to immediate patient safety, AI enhances the long-term monitoring of patients by predicting therapeutic outcomes and relapse risk. Through sophisticated algorithms that integrate genomic, proteomic, and metabolic data, AI is instrumental in identifying patients at risk for recurrence. Predictive modeling can guide follow-up care, suggesting additional interventions or alternative therapies as needed. These approaches not only increase the safety and effectiveness of CAR-T treatments but also provide a more sustainable, individualized approach to post-therapy management.[15]

The integration of AI into CAR-T cell therapy represents a significant advancement in precision medicine, facilitating highly individualized treatment protocols. By synthesizing patient-specific data from diverse sources-such as genetic profiles, cellular characteristics, and clinical biomarkers-AI constructs a comprehensive patient profile that optimally guides each stage of the therapeutic process.[16] This data-driven, tailored approach ensures that CAR-T therapy precisely targets cancer cells while aligning with the patient's unique biological profile, thereby minimizing adverse reactions and maximizing therapeutic efficacy. Additionally, AI-enhanced CRISPR-Cas9 technology further advances CAR-T therapy by reducing off-target gene edits, thereby increasing treatment safety and expanding the applicability of CAR-T cells to target solid tumors and a broader array of cancer types.[17,18]

The future of AI-driven CAR-T therapy holds promising potential for further personalization.[19] Emerging research is focused on using AI to dynamically adapt CAR-T cell dosages and combinations with other immunotherapies in real-time based on a patient's response to treatment.[20] This adaptability could lead to even greater efficacy in fighting resistant cancer types and improving patient quality of life. As AI technologies evolve, they are expected to seamlessly integrate with healthcare practices, making personalized CAR-T therapy a practical reality for broader patient populations.

As AI-driven technologies continue to evolve, the potential for CAR-T therapy to offer truly personalized cancer treatments expands. Current research explores how AI might predict not only adverse effects and therapeutic efficacy but also patient-specific therapeutic timelines.[21] Through deep learning and machine learning algorithms, AI is enabling CAR-T therapy to adapt dynamically over time, adjusting to each patient's unique physiological responses to optimize therapeutic outcomes.[22] With this adaptability, CAR-T cells may one day be capable of on-the-fly adjustments in dosage, timing, and even genetic modifications based on real-time feedback from the patient's condition, ensuring precision on an unprecedented scale.[23,24]

In clinical practice, AI-enabled digital twins—virtual models that replicate the biological systems of CAR-T patients—are starting to simulate individual responses to CAR-T therapy, allowing clinicians to test and tweak treatment variables without risk to the patient. These digital twins are created by integrating a range of patient data, including genomic information, immune system biomarkers, and treatment response histories, into predictive AI models. By simulating how a specific CAR-T therapy might interact with a patient's unique biology, digital twins empower clinicians to refine treatment protocols for better precision.[25–27]

Moreover, as CAR-T therapy continues to expand beyond hematologic malignancies to solid tumors, AI plays a pivotal role in overcoming the challenges specific to these cancers. Solid tumors present obstacles like physical barriers and immunosuppressive microenvironments, which can reduce CAR-T efficacy.[28] AI is being harnessed to identify and engineer CAR-T cells with enhanced targeting capabilities and adaptability to the tumor environment, allowing these cells to penetrate and function effectively within solid tumors. This marks a significant shift in CAR-T therapy applications, broadening its scope to a wider array of cancer types.[29,30]

Conclusion

Ultimately, as AI-driven CAR-T therapy develops, there are implications for regulatory and ethical frameworks. AI introduces complex considerations around data security, patient consent, and algorithmic transparency.[31] As treatment becomes more individualized, ensuring that AI models operate fairly and safely across diverse patient populations will be essential. Regulations are adapting to meet these challenges, with AI governance frameworks emerging to safeguard patient rights and ensure equitable access to advanced therapies.

Acknowledgments

None.

Conflicts of interest

The authors declare that there are no conflicts of interest.

References

1. Banerjee R, Shah N, Dicker AP. Next-generation implementation of chimeric antigen receptor T-cell therapy using digital health. *JCO Clin Cancer Informatics*. 2021;5:668–678.
2. Santomasso BD, Nastoupil LJ, Adkins S, et al. Management of immune-related adverse events in patients treated with chimeric antigen receptor T-cell therapy: ASCO guideline. *J Clin Oncol*. 2021;39(35):3978–3992.
3. Tedesco VE, Mohan C. Biomarkers for predicting cytokine release syndrome following CD19-targeted CAR T cell therapy. *J Immunol*. 2021;206(7):1561–1568.
4. Turicek DP, Giordani VM, Moraly J, et al. CAR T-cell detection scoping review: An essential biomarker in critical need of standardization. *J Immunother Cancer*. 2023;11:e006596.
5. Menon AP, Moreno B, Meraviglia-Crivelli D, et al. Modulating T cell responses by targeting CD3. *Cancers (Basel)*. 2023;15(4):1189.
6. Nettleton DF, Mari Buye N, Marti Soler H, et al. Smart sensor control and monitoring of an automated cell expansion process. *Sensors (Basel, Switzerland)*. 2023;23(24):9676.
7. Zhang C, Zhou G, Jing Y, et al. A digital twin-based automatic programming method for adaptive control of manufacturing cells. *IEEE Access*. 2022;10:80784–80793.
8. Sun Q, Ge Z. A survey on deep learning for data-driven soft sensors. *IEEE Trans Ind Informatics*. 2021;17:5853–5866.
9. Schiemer R, Weggan JT, Schmitt KM, et al. An adaptive soft-sensor for advanced real-time monitoring of an antibody-drug conjugation reaction. *Biotechnol Bioeng*. 2023;120:1914–1928.
10. Yu Q, Xhnag Y, Zhao H, et al. A robust optimal scheduling system based on multi-performance driving for complex manufacturing systems. *Sci Rep*. 2023;13(1):16911.
11. Nukala U, Rodriguez Messan M, Yogurtcu ON, et al. A systematic review of the efforts and hindrances of modeling and simulation of CAR T-cell therapy. *AAPS J*. 2021;23(3):52.
12. Hort S, Herbst L, Vackel N, et al. Toward rapid, widely available autologous CAR-T cell therapy-– Artificial intelligence and automation enabling the smart manufacturing hospital. *Front Med*. 2022;9:913287.
13. Shaik T, Tao X, Higgins N, et al. Remote patient monitoring using artificial intelligence: Current state, applications, and challenges. *WIREs Data Mining Knowl Discov*. 2023;13(2):e1485.
14. Paludo J, Bansal R, Holland AT, et al. Pilot implementation of remote patient monitoring program for outpatient management of CAR-T cell therapy. *Blood*. 2021.
15. Schena FP, Manno C, Strippoli GFM. Understanding patient needs and predicting outcomes in IgA nephropathy using data analytics and artificial intelligence: A narrative review. *Clin Kidney J*. 2023;16(Suppl 2):ii55-ii61.
16. Boretti A. Improving chimeric antigen receptor T-cell therapies by using artificial intelligence and internet of things technologies: A narrative review. *Eur J Pharmacol*. 2024;974:176618.
17. Bäckel N, Hort S, Kis T, et al. Elaborating the potential of artificial intelligence in automated CAR-T cell manufacturing. *Front Mol Med*. 2023;3:1250508.
18. Boretti A. The transformative potential of AI-driven CRISPR-Cas9 genome editing to enhance CAR T-cell therapy. *Comput Biol Med*. 2024;182:109137.
19. Strzelec A, Helbig G. Are we ready for personalized CAR-T therapy? *Eur J Haematol*. 2023;112(2):174–183.
20. Cai Q, Wearren S, Pietrobon V, et al. Building smart CAR T-cell therapies: The path to overcome current challenges. *Cancer Cell*. 2023;41(10):1689–1695.
21. Bäckel N, Hort S, Kis T, et al. Elaborating the potential of artificial intelligence in automated CAR-T cell manufacturing. *Front Mol Med*. 2023;3:1250508.
22. Bhinder B, Gilvary C, Madhukar NS, et al. Artificial intelligence in cancer research and precision medicine. *Cancer Discov*. 2021;11(4):900–915.

23. Dagar G, Gupta A, Masoodi T, et al. Harnessing the potential of CAR-T cell therapy: Progress, challenges, and future directions in hematological and solid tumor treatments. *J Transl Med*. 2023;21(1):449.

24. Baker DJ, Arany Z, Baur JA, et al. CAR T therapy beyond cancer: The evolution of a living drug. *Nature.* 2023;619(7971):707–715.

25. Turab M, Jamil S. A comprehensive survey of digital twins in healthcare in the era of metaverse. *BioMedInformatics*. 2023;3(3):563–584.

26. Attaran M, Celik BG. Digital twin: Benefits, use cases, challenges, and opportunities. *Decis Anal J*. 2023:6.

27. Katsoulakis E, Wang Q, Wu H, et al. Digital twins for health: A scoping review. *NPJ Digit Med*. 2024;7(1):77.

28. Hou AJ, Chen LC, Chen YY. Navigating CAR-T cells through the solid-tumour microenvironment. *Nat Rev Drug Discov.* 2021;20(7):531–550.

29. Peng L, Sferruzza G, Yang L, et al. CAR-T and CAR-NK as cellular cancer immunotherapy for solid tumors. *Cell Mol Immunol*. 2024;21(10):1089–1108.

30. Chen T, Wag M, Chen Y, et al. Current challenges and therapeutic advances of CAR-T cell therapy for solid tumors. *Cancer Cell Int.* 2024;24(1):133.

31. Williamson SM, Prybutok V. Balancing privacy and progress: A review of privacy challenges, systemic oversight, and patient perceptions in AI-driven healthcare. *Appl Sci.* 2024;14(2):675.