Secure and Decentralized Collaboration in Oncology: A Blockchain Approach to Tumor Segmentation

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***Abstract*—This research presents an innovative framework that uses blockchain technology to improve tumor segmentation in medical imaging. The approach tackles issues related to data security, particularly when dealing with real private dataset, annotation accuracy, and collaboration. With the growing reliance of the medical industry on accurate tumor segmentation from medical images for cancer diagnosis and treatment, current methods are inadequate in maintaining data accuracy and promoting collaboration among experts across different countries. Our suggested approach utilizes blockchain technology to establish a decentralized, secure platform for the collaborative obtaining, annotation, and validation of medical images by data scientists, oncologists, and radiologists. Smart contracts streamline essential procedures such as verification of annotations, consensus among experts, and remuneration of contributors, guaranteeing the dependability and excellence of the data. Furthermore, the unchangeable record of transactions in the blockchain ensures a reliable basis for implementing artificial intelligence and machine learning algorithms. This improves the accuracy of segmenting data and allows for predictive modeling. This strategy not only improves the precision and effectiveness of tumor segmentation but also promotes a worldwide collaborative environment, which has the potential to revolutionize cancer diagnostics and treatment planning. Furthermore, it ensures the privacy and security of patient data.**

***Keywords*—Blockchain Technology, Decentralized Healthcare Systems, Collaborative Annotation, Medical image processing, Data Security and Privacy.**

I. Introduction

Medical imaging is a crucial component of oncology, allowing us to observe the hidden complexities of the human body and playing a vital role in identifying, diagnosing, and treating cancer. Medical imaging techniques such as MRI, CT scans, and PET scans provide clinicians with a comprehensive understanding of tumor structure, position, and the possible dissemination of cancer cells [1], [2], [3]. This information is essential for developing successful treatment strategies. Advancements in digital technology and artificial intelligence have greatly improved the accuracy of these imaging modalities. This has resulted in enhanced image resolution, faster processing times, and the ability to detect subtle physiological changes that may indicate the early presence of malignancy [4], [5], [6].

Tumor segmentation is an essential step in oncological imaging, as it plays a critical role in precisely measuring tumor size, monitoring its pace of growth, and analyzing its reaction to treatment. This procedure involves precisely identifying the boundaries of tumors inside medical imaging to differentiate them from the surrounding healthy tissues. There are several difficulties with this task because it traditionally required manual intervention by highly qualified radiologists. Initially, the process of manual segmentation is extremely time-consuming and requires a significant amount of effort, resulting in potential delays in both diagnosis and treatment planning. Moreover, the outcomes of manual segmentation may range considerably across various specialists as a consequence of subjective interpretation.

To tackle these problems, there have been recent breakthroughs in the advancement of automated and semi-automatic segmentation algorithms. These algorithms utilize state-of-the-art machine learning and deep learning approaches, offering tools that are not only faster but also more reliable and less susceptible to human mistakes. These tools are specifically created to improve the precision, durability, and consistency of tumor segmentation, making it easier to obtain more dependable measurements and evaluations. Furthermore, these algorithms possess the ability to effectively manage substantial amounts of data, making them highly helpful in clinical environments where rapid response times are crucial. By implementing automated segmentation, these technologies also contribute to the standardization of evaluations across various healthcare facilities, thereby enhancing the overall quality of cancer care [7], [8].

Nevertheless, these technical breakthroughs also give rise to novel obstacles. The efficacy of automated segmentation systems may be constrained by the quality and amount of the data utilized for their training, emphasizing the significance of having access to extensive, meticulously labeled medical imaging datasets. Furthermore, the incorporation of these sophisticated tools into clinical workflows gives rise to concerns regarding data privacy, security, and the necessity for strong validation frameworks to guarantee compliance with therapeutic standards [2], [5].

Blockchain technology is a revolutionary option for addressing the crucial problems of data privacy, security, and collaboration in the field of medical image processing. Implementing a decentralized ledger system that disperses data over a network, guarantees the integrity and security of medical images, effectively preventing illegal access or modifications. This resilient structure not only secures confidential patient data but also cultivates a sense of collaboration among healthcare practitioners [9], [10], [11]. By utilizing smart contracts, blockchain technology facilitates the effortless and secure exchange and annotation of medical images. This enables radiologists, oncologists, and data scientists from around the globe to collaborate on tumor segmentation projects while ensuring the confidentiality of sensitive data. In addition, blockchain technology improves the ability of different systems to work together and allows for easier access to a variety of datasets. This speeds up the creation of advanced diagnostic tools that are powered by artificial intelligence.

The main objective of this study is to introduce a new framework that uses blockchain technology to facilitate secure and decentralized communication between radiologists, doctors, clinicians, and data scientists when using real private medical data. The platform can be specifically developed to improve tumor segmentation in medical imaging.

II. Fundamentals of Blockchain Technology

A collection of fundamental components underpin blockchain technology, which collectively establishes its unique attributes of transparency, decentralization, and security. Comprehending these components is essential for understanding how blockchain has the potential to revolutionize many fields, such as medical image processing [12], [13].

The structure of a blockchain is comprised of a sequence of data blocks that are securely interconnected by cryptographic principles. Every block consists of a set of transactions, which, in the context of medical imaging, could encompass activities like uploading a new image, annotating an image, or accessing an image for analysis. Importantly, each block contains a cryptographic hash of the preceding block, resulting in an unchangeable chain. The integrity of the data is protected by this structure, as modifying the content of a block after it has been added to the chain would necessitate recalculating the hashes of all following blocks [12], [14].

Decentralization is an essential concept of blockchain technology. A blockchain differs from standard databases by distributing its data over a network of computers (nodes), instead of storing all data on a central server. Every node in the network stores a complete copy of the blockchain, and all nodes must agree on new blocks and transactions to validate them. This consensus technique guarantees that no individual party possesses complete authority over the entire blockchain, thus minimizing the potential for data manipulation, censorship, and centralized vulnerabilities. Decentralization in medical image processing refers to the absence of a central authority governing the data, allowing for secure and fair distribution of medical images among approved entities [13], [15].

Encryption is crucial for maintaining data security on a blockchain. Two main types of encryption are commonly used: asymmetric encryption, sometimes known as public-key cryptography and cryptographic hashing. Asymmetric encryption guarantees safe communication between nodes inside the blockchain network. Every participant possesses a set of keys: a public key, which can be disclosed to everyone, and a private key, which is safeguarded confidentially. This mechanism enables data encryption using the receiver's public key and can only be decrypted using their private key, guaranteeing that only the intended recipient may retrieve the information. Cryptographic hashing is employed to ensure the security of the blocks' data and establish secure connections between the blocks [15], [16].

A hash function is a computational algorithm that takes input data and generates a deterministic fixed-size string of bytes, known as the hash, which exhibits the properties of randomness. Even the slightest alteration to the supplied data leads to a significantly distinct hash, allowing for the identification of data manipulation. The hashing technique is essential for preserving the integrity of the blockchain, guaranteeing that recorded data remains unaltered and undetectable if tampered with. The combination of design, decentralization, and encryption gives blockchain its distinct characteristics, making it a suitable platform for safe, transparent, and collaborative tasks like processing and analyzing medical images [11], [14].

III. Collaborative Tumor Segmentation and Medical Imaging

To address the difficulties and needs of contemporary medical imaging, particularly in the field of brain tumor segmentation, we suggest a cooperative framework supported by blockchain technology. This framework is specifically developed to ensure the security and efficiency of the entire process, especially when dealing with private medical data, starting from image acquisition to annotation and analysis. It utilizes the advantages of blockchain technology to improve cooperation, data security, and the accuracy of annotations.

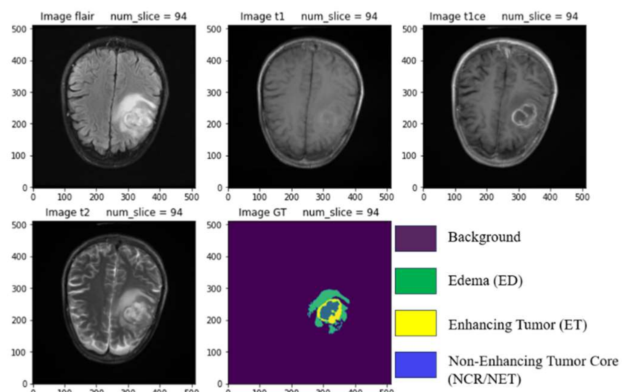

Fig. 1. One sample of different brain MRI modalities from a private dataset.

During the initial stage of the tumor segmentation workflow, radiologists and medical imaging professionals utilize advanced imaging techniques to acquire precise images of tumors in the human body. MRI is employed for its outstanding capacity to discern between soft tissues, making it well-suited for visualizing brain malignancies, spinal cord abnormalities, and soft tissue tumors. CT scans provide a faster way to obtain cross-sectional images, which give important details on the size, shape, and position of tumors, as well as their proximity to nearby structures. Positron Emission Tomography (PET) scans are highly valuable for providing metabolic information about tumor activity, aiding in the identification of the most active region within a tumor. As represented by a sample of various brain MRI modalities depicted in Fig. 1 from a private dataset, these imaging techniques play a crucial role in achieving the precise segmentation of tumors. This dataset obtained from the Ankara Bilkent City Hospital. Ethical approval was already obtained from Ankara Yildirim Beyazit University Ethical Committee for the the exclusive use of this data for research purposes.

After obtaining these high-resolution images, the subsequent crucial task is to secure this extremely delicate data. The images are encrypted using advanced cryptographic techniques, specifically asymmetric encryption. Encrypting medical images before uploading them to the blockchain is not just a technical process, but a vital step in maintaining patient confidentiality and ensuring the integrity of the data. It guarantees that personal health information is carefully safeguarded, addressing any worries regarding privacy and data abuse in the era of digital technology. This approach ensures the establishment of a secure foundation for the subsequent phases of the collaborative framework by securing the data from the beginning. It guarantees that all activities, including annotation by medical experts and detailed analysis by data scientists, are conducted on a platform that is trustworthy and secure. The thorough focus on data security highlights the dedication to upholding the highest levels of patient care and research integrity during the tumor segmentation process.

After securely uploading encrypted medical images to the blockchain, a complex access control mechanism is implemented to enable the next important step: the annotation of these images by a specific set of medical professionals. This group consists of radiologists, who specialize in analyzing medical images to detect and diagnose problems, and oncologists, who offer knowledge on the characteristics and therapeutic implications of discovered tumors. Their collaboration is crucial in precisely defining tumor boundaries, a process that greatly impacts later treatment planning and prognosis evaluation.

The access control system is effectively administered by using smart contracts on the blockchain. Smart contracts are automated contracts where the agreement between the buyer and seller is encoded directly into lines of code, allowing for self-execution. Within this particular setting, they serve as gatekeepers that autonomously enforce access regulations. Before allowing an expert to see or make notes on an image, the smart contract validates their qualifications based on a predetermined set of standards. This may involve confirming the validity of medical licenses, specialized credentials, and potentially previous contributions to the dataset of the blockchain. The smart contract only allows access to the encrypted images after successful verification, enabling the authorized expert to decrypt and comment on them. Pseudo Code of Smart Contracts in the Collaborative Framework is depicted in Fig. 2.

The rigorous procedure of verifying credentials and controlling access guarantees that every image is annotated by the most skilled experts, hence improving the quality and dependability of the dataset. Furthermore, this strategy greatly enhances the privacy and security foundation of the entire system. By implementing stringent measures to restrict access to critical medical images to only qualified and authorized persons, the risk of unauthorized viewing or data breaches is significantly minimized. Moreover, the unchangeable characteristic of blockchain technology ensures that every instance of accessing and annotating is documented, forming a traceable path that strengthens responsibility and transparency in the procedure.

When an image is annotated by numerous experts and there are disagreements in their opinions or interpretations, smart contracts are used to trigger a consensus mechanism. This technique is specifically developed to resolve these discrepancies, thereby guaranteeing the integrity of the dataset. One possible approach is to convene a group of specialists to examine the various annotations and determine the most precise version through a voting process. Alternatively, an algorithmic method may be employed to assess the annotations against a predetermined set of criteria. The objective is to synchronize the annotations, reaching a consensus that accurately and effectively represents the segmentation of the tumor. This technique not only improves the quality of the dataset but also promotes collaboration and debate among experts, which helps to continuously better annotation practices.

Smart contracts simplify the pay process for experts by incentivizing and rewarding their contributions according to preset criteria. This may encompass quantitative indicators, such as the number of images that an expert has annotated, or qualitative evaluations, such as the quality of the annotations as ascertained through peer review or the results of the consensus-building procedure. Compensation might be diverse, ranging from monetary rewards to recognition within the scientific community to privileges to use advanced services on the site. Smart contracts guarantee transparency and fairness in compensating contributors by precisely defining criteria and automating the compensation process. This encourages continued participation and promotes the expansion of the annotated dataset.

Once a dataset is authenticated and secured using blockchain technology, data scientists have an ideal environment to use powerful AI and machine learning algorithms. This crucial stage utilizes abundant, annotated images to enhance medical research and diagnostic capacities in many significant ways.

Data scientists employ the dataset to enhance or create new tumor segmentation algorithms that are more precise and effective. Through the process of training, these algorithms are exposed to a varied and precisely labeled collection of images. This enables the models to enhance their ability to distinguish between tumor tissues and the healthy tissues surrounding them, even in situations when the differences are not easily noticeable. This training process utilizes advanced techniques such as deep learning, in which neural networks acquire knowledge from extensive datasets, progressively enhancing their ability to accurately segment through iterative feedback and modifications. The objective is to attain a degree of accuracy that matches or exceeds that of human specialists, hence improving the diagnostic procedure and facilitating customized treatment strategies.

```
pragma solidity ^0.8.0;

contract TumorSegmentationFramework {
    struct Image {
        string imageHash; // Hash of the encrypted image for security
        address uploader; // Address of the radiologist who uploaded the image
        bool isAnnotated; // Flag to check if the image has been annotated
        bool isProcessed; // Flag to check if the image has been processed
    }

    struct Annotation {
        string annotationData; // Encrypted data or hash of the annotation
        address[] annotators; // Addresses of experts who contributed to the annotation
        bool isValidated; // Whether the annotation has been validated
    }

    struct AnalysisResult {
        string resultData; // Encrypted data or hash of the analysis result
        address analyst; // Address of the data scientist who analyzed the image
    }

    mapping(uint => Image) public images; // Mapping of image IDs to Image structs
    mapping(uint => Annotation) public annotations; // Mapping of image IDs to Annotation structs
    mapping(uint => AnalysisResult) public analysisResults; // Mapping of image IDs to AnalysisResult structs

    // 1. Image Obtaining
    function uploadImage(string memory _imageHash) public {
        // Implementation for uploading an encrypted image to the blockchain
        // Set the isAnnotated and isProcessed flags to false initially
    }

    // 2. Image Annotating
    function annotateImage(uint _imageId, string memory _annotationData, address _annotator) public {
        // Implementation for experts to annotate an image
        // Include validation checks to ensure only authorized experts can annotate
        // Update the isAnnotated flag once the annotation is complete and validated
    }

    // Validation of Annotations
    function validateAnnotation(uint _imageId) private {
        // Implementation for validating the annotation
        // This could involve consensus mechanisms among experts
        // Update the isValidated flag upon successful validation
    }

    // 3. Image Processing
    function processImage(uint _imageId, string memory _resultData, address _analyst) public {
        // Implementation for data scientists to submit their analysis of the annotated images
        // Ensure the image has been annotated and validated before processing
        // Update the isProcessed flag once analysis is complete
    }

    // Utility Functions (e.g., access control, consensus mechanism, compensation)
    // Include functions for controlling access based on roles, building consensus on annotations,
    // and compensating contributors based on predefined criteria.
```

Fig. 2. Pseudo Code for Smart Contracts in the Collaborative Framework.

In addition to segmentation, the dataset is used for predictive modeling. Data scientists utilize statistical and machine learning approaches to forecast outcomes such as tumor progression, patient response to different treatment procedures, or the probability of recurrence. These models can examine patterns and correlations within the dataset, uncovering insights that may not be readily obvious to human observers. By comprehending these patterns, medical professionals can make more knowledgeable choices, customize treatments for each patient, and potentially enhance prognoses.

Importantly, the entire analytical process is supported by the blockchain's unchangeable record, which guarantees the reliability and protection of the data. Every image, annotation, and subsequent analysis result is meticulously documented on the blockchain, forming an immutable history record. The immutability of the data ensures that data scientists are dealing with the original, unaltered data, thereby maintaining the accuracy and integrity of their studies. Furthermore, the robust security features of blockchain technology guarantee the preservation of patient confidentiality and safeguard the data from any unwanted access or modification.

The differentiation between a permissioned and permissionless blockchain is of utmost importance, especially when it comes to managing sensitive medical data. Permissioned blockchains exclusively permit authorized users to become part of the network, rendering them well-suited for applications that necessitate elevated degrees of privacy and security, such as the management of medical data. In contrast, permissionless blockchains provide unrestricted access to anybody, potentially resulting in reduced control over data access and security. The suggested system, with its focus on protecting confidential medical data and validating credentials via smart contracts, is expected to gain advantages from a permissioned blockchain. This configuration guarantees that solely authenticated healthcare professionals can gain entry to and make comments on the medical images, hence upholding stringent security and privacy protocols.

Role-based access control (RBAC) in blockchain can be resource-intensive, particularly when it comes to gas consumption and computing costs. Whenever access control logic is executed on the blockchain, such as for credential verification or logging access events, it utilizes computational resources and incurs gas costs. Gas is a price paid to account for the computational energy expended. To enhance these aspects, the authors could investigate various strategies: 1) State Channels: This technique minimizes the number of transactions that must be handled on-chain by using state channels for microtransactions that only settle on the blockchain following several processes. 2) Efficient Contract Design: Maximizing the efficiency of smart contract code by minimizing on-chain processes. 3) Layered Architecture: Utilizing off-chain computations whenever feasible and reserving the blockchain just for actions that require finality and security.

Also, standards must also be developed in accordance with prevailing medical and data protection regulations, including but not limited to HIPAA in the United States, GDPR in Europe, and analogous frameworks across the globe. Compliance guarantees the legal soundness of the blockchain application and safeguards the privacy and rights of patients.

IV. Conclusion

To summarize, the incorporation of blockchain technology in medical image processing, particularly for tumor segmentation, brings in a new era of innovation, security, and collaboration in the healthcare field. This research has demonstrated how a secure and decentralized system can improve the accuracy, reliability, and efficiency of tumor segmentation operations while preserving patient privacy. Blockchain technology guarantees the security and privacy of sensitive medical information, while simultaneously promoting a cooperative atmosphere where doctors, oncologists, and data scientists may share their knowledge and skills worldwide.

Incorporating smart contracts into this framework will enable the annotation of image data without the need for anonymization. This, in turn, facilitates the inclusion of necessary additional clinical data when required, thereby enhancing diagnostic accuracy and the development of individualized treatment plans. Furthermore, essential tasks like verifying annotations, reaching consensus, and compensating contributors are automated. This results in a more efficient workflow and guarantees the utilization of only top-notch data. This method greatly diminishes the likelihood of errors and inconsistencies in tumor segmentation.

Moreover, the proficiency of data scientists in utilizing AI and machine learning algorithms on a verified and protected dataset enhances the possibilities for progress in medical research. The accuracy of tumor segmentation algorithms and the advancement of predictive models have the potential to revolutionize patient care by allowing for earlier detection and more efficient treatment approaches.

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References

[1] R. Ranjbarzadeh, P. Zarbakhsh, A. Caputo, E. B. Tirkolaee, and M. Bendechache, "Brain Tumor Segmentation based on an Optimized Convolutional Neural Network and an Improved Chimp Optimization Algorithm," Oct. 2022, doi: 10.21203/RS.3.RS-2203596/V1.

[2] R. Ranjbarzadeh, A. Caputo, E. B. Tirkolaee, S. Jafarzadeh Ghoushchi, and M. Bendechache, "Brain tumor segmentation of MRI images: A comprehensive review on the application of artificial intelligence tools," Comput Biol Med, vol. 152, p. 106405, Jan. 2023, doi: 10.1016/J.COMPBIOMED.2022.106405.

[3] M. Bakhshi, A. Karkehabadi, and S. B. Razavian, "Revolutionizing Medical Diagnosis with Novel Teaching-Learning-Based Optimization," 2024 International Conference on Emerging Smart Computing and Informatics, ESCI 2024, 2024, doi: 10.1109/ESCI59607.2024.10497216.

[4] Z. Liu et al., "Deep learning based brain tumor segmentation: a survey," Complex and Intelligent Systems, pp. 1–26, Jul. 2022, doi: 10.1007/S40747-022-00815-5/TABLES/5.

[5] R. Ranjbarzadeh et al., "Breast tumor localization and segmentation using machine learning techniques: Overview of datasets, findings, and methods," Comput Biol Med, vol. 152, p. 106443, Jan. 2023, doi: 10.1016/J.COMPBIOMED.2022.106443.

[6] A. Karkehabadi, P. Oftadeh, D. Shafaie, and J. Hassanpour, "On the Connection between Saliency Guided Training and Robustness in Image Classification," 2024 12th International Conference on Intelligent Control and Information Processing, ICICIP 2024, pp. 203–210, 2024, doi: 10.1109/ICICIP60808.2024.10477811.

[7] S. Bakas et al., "Identifying the Best Machine Learning Algorithms for Brain Tumor Segmentation, Progression Assessment, and Overall Survival Prediction in the BRATS Challenge," Nov. 2018, Accessed: Sep. 14, 2021. [Online]. Available: https://arxiv.org/abs/1811.02629v3

[8] H. M. Balaha and A. E. S. Hassan, "A variate brain tumor segmentation, optimization, and recognition framework," Artif Intell Rev, vol. 56, no. 7, pp. 7403–7456, Jul. 2023, doi: 10.1007/S10462-022-10337-8/TABLES/12.

[9] H. B. Mahajan and A. A. Junnarkar, “Smart healthcare system using integrated and lightweight ECC with private blockchain for multimedia medical data processing,” Multimed Tools Appl, vol. 82, no. 28, pp. 44335–44358, Nov. 2023, doi: 10.1007/S11042-023-15204-4/TABLES/10.

[10] J. Miao, Z. Wang, Z. Wu, X. Ning, and P. Tiwari, “A blockchain-enabled privacy-preserving authentication management protocol for Internet of Medical Things,” Expert Syst Appl, vol. 237, p. 121329, Mar. 2024, doi: 10.1016/J.ESWA.2023.121329.

[11] M. El Khatib, H. M. Alzoubi, S. Hamidi, A. Baydoun, A. Al-Nakeeb, and M. Alshurideh, “Impact of Using the Internet of Medical Things on e-Healthcare Performance: Blockchain Assist in Improving Smart Contract,” ClinicoEconomics and Outcomes Research, vol. 15, pp. 397–411, 2023, doi: 10.2147/CEOR.S407778.

[12] H. Taherdoost, “The Role of Blockchain in Medical Data Sharing,” Cryptography 2023, Vol. 7, Page 36, vol. 7, no. 3, p. 36, Jul. 2023, doi: 10.3390/CRYPTOGRAPHY7030036.

[13] K. P. Tran, Y. Man, Z. He, and H. Taherdoost, “Blockchain-Based Internet of Medical Things,” Applied Sciences 2023, Vol. 13, Page 1287, vol. 13, no. 3, p. 1287, Jan. 2023, doi: 10.3390/APP13031287.

[14] Z. S. Chen, Z. Zhu, Z. J. Wang, and Y. Tsang, “Fairness-aware large-scale collective opinion generation paradigm: A case study of evaluating blockchain adoption barriers in medical supply chain,” Inf Sci (N Y), vol. 635, pp. 257–278, Jul. 2023, doi: 10.1016/J.INS.2023.03.135.

[15] H. Tian, J. He, and Y. Ding, “Medical Data Management on Blockchain with Privacy,” J Med Syst, vol. 43, no. 2, pp. 1–6, Feb. 2019, doi: 10.1007/S10916-018-1144-X/FIGURES/2.

[16] J. Liu, Y. Fan, R. Sun, L. Liu, C. Wu, and S. Mumtaz, “Blockchain-Aided Privacy-Preserving Medical Data Sharing Scheme for E-Healthcare System,” IEEE Internet Things J, vol. 10, no. 24, pp. 21377–21388, Dec. 2023, doi: 10.1109/JIOT.2023.3287636.