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RESEARCH ARTICLE

Explainable AI Models for Forensic Endodontics: Linking Root Canal Patterns to Individual Dental Identity

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ABSTRACT

Forensic endodontics relies on the unique anatomical features of teeth, particularly root canal morphology, to assist in individual identification. Recent advances in artificial intelligence (AI) offer powerful tools to analyze complex dental patterns; however, the "black-box" nature of many AI models limits their applicability in legal and forensic contexts. This study explores the development of explainable AI (XAI) models designed to link root canal configurations to individual dental identities. By integrating high-resolution dental imaging data with interpretable machine learning approaches, the proposed framework not only achieves accurate pattern recognition but also provides transparent insights into model decisions, enabling forensic practitioners to validate and justify identification outcomes. The findings demonstrate that XAI can bridge the gap between advanced computational analysis and forensic accountability, offering a robust, ethical, and legally defensible methodology for dental identification.

Keywords: Forensic endodontics, explainable AI, root canal morphology, dental identification, interpretable machine learning, pattern recognition, forensic dentistry.

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INTRODUCTION

Forensic dentistry plays a critical role in human identification, particularly in scenarios where conventional methods such as fingerprinting or DNA analysis are unavailable or compromised. Among dental features, root canal morphology offers a uniquely individualized pattern that can be leveraged for personal identification due to its high variability and resistance to postmortem changes (Girijan et al., 2023). Traditional forensic methods rely heavily on expert interpretation of radiographs and clinical observations, which can be time-consuming, subjective, and prone to error.

Recent advances in artificial intelligence (AI) have opened new avenues for enhancing the accuracy and efficiency of forensic dental identification. AI, particularly deep learning models, has demonstrated significant potential in analyzing complex dental images, detecting anatomical structures, and classifying root canal patterns (Singh, 2022; Bagde, 2021). Studies have applied convolutional neural networks (CNNs) to dental panoramic radiographs and periapical images, achieving automated detection of teeth and root canal configurations with high precision (최혜란, 2022; Haghanifar, 2022). Furthermore, AI models have been tailored for forensic applications, enabling the recognition of individual dental patterns as a reliable biometric trait (Liang et al., 2021; Marín Estañ, 2022).

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Despite these advances, the "black-box" nature of many AI models presents challenges for forensic practice, where interpretability and transparency are crucial for legal and ethical validation. Explainable AI (XAI) approaches provide mechanisms to interpret and visualize model decisions, making it possible to link specific root canal features to individual identity while maintaining forensic rigor (Yang et al., 2022). By integrating XAI into forensic endodontics, it becomes feasible to develop systems that not only automate identification but also provide interpretable evidence that can withstand legal scrutiny.

This convergence of forensic dentistry and explainable AI promises a transformative approach to human identification, leveraging the distinctiveness of root canal patterns as a secure and scientifically defensible biometric marker (Girijan et al., 2023; Singh, 2022).

BACKGROUND

Forensic endodontics is a specialized branch of forensic dentistry that leverages the unique morphological characteristics of teeth, particularly root canal anatomy, for human identification. Root canal systems exhibit high inter-individual variability in terms of shape, curvature, number of canals, and branching patterns, making them reliable anatomical markers for personal identification in medico-legal contexts (Girijan et al., 2023). Traditional forensic dental identification relies heavily on manual comparison of dental radiographs, which is often labor-intensive, time-consuming, and dependent on the expertise of the practitioner. The need for faster, more accurate, and reproducible methods has prompted interest in computational and AI-assisted approaches.

Artificial intelligence (AI), particularly deep learning, has increasingly been applied in endodontics to automate the analysis of dental images and extract clinically relevant features (Singh, 2022; Bagde, 2021). AI models, such as convolutional neural networks (CNNs), have demonstrated significant potential in detecting root canal morphology, classifying canal types, and identifying dental pathologies from periapical and panoramic radiographs (Yang et al., 2022; Haghanifar, 2022). These models not only improve diagnostic accuracy but also reduce observer variability, a critical factor in forensic identification scenarios.

Recent studies have explored the use of AI specifically for forensic dental identification. CNN-based models have been employed to construct automated human identification systems from dental radiographs, achieving promising results in differentiating individuals based on unique dental patterns (최혜란, 2022; Marín Estañ, 2022; Liang et al., 2021). Such approaches capitalize on the inherent uniqueness of dental features, including root canal configurations, crown morphology, and radiographic density patterns, enabling high-confidence matches between antemortem and postmortem records.

Despite the advances in AI-assisted endodontics, explainability remains a critical concern. For forensic applications, it is not sufficient for an AI system to make a correct prediction; the rationale behind its decision must be interpretable to satisfy legal and scientific scrutiny (Yang et al., 2022). Visually explainable models, which highlight specific anatomical regions influencing the prediction, have shown promise in bridging this gap between AI accuracy and forensic reliability. These developments underscore the importance of integrating explainable AI (XAI) frameworks in forensic endodontics to ensure transparency, accountability, and admissibility in legal contexts.

Collectively, the integration of AI and forensic endodontics represents a transformative approach to human identification, combining the anatomical uniqueness of root canal systems with the computational power of modern AI, while addressing the need for interpretability in sensitive medico-legal applications.

METHODOLOGY (HIGH-LEVEL)

The methodology for developing explainable AI (XAI) models for forensic endodontics involves several interconnected stages, aimed at linking individual root canal patterns to human identity.

Data Acquisition and Preprocessing

Data for this study are sourced from panoramic and periapical radiographs, as well as cone-beam computed tomography (CBCT) scans, capturing the full spectrum of root canal morphologies. Emphasis is placed on ensuring diversity in age, sex, and dental anatomy to reflect real-world forensic scenarios (Girijan et al., 2023). Preprocessing steps include noise reduction, image normalization, and segmentation of individual teeth and root canal structures, following established protocols for automated teeth extraction (Haghanifar, 2022).

Feature Extraction

Key morphological features are extracted to represent root canal anatomy, including canal number, curvature, branching patterns, and root length. Advanced computer vision techniques are employed to encode these patterns into numerical representations suitable for machine learning models (Singh, 2022; Bagde, 2021). The extraction process is designed to preserve individual-specific variations, which are critical for forensic identification (Yang et al., 2022).

AI Model Selection

Explainable AI models are prioritized to ensure transparency and interpretability of identification decisions. Approaches include attention-based convolutional neural networks (CNNs), decision trees, and hybrid models that combine deep learning with rule-based systems (Liang et al., 2021; 최혜란, 2022). Model selection is guided by the dual objectives of high accuracy in identification and the ability to visualize decision pathways for forensic validation (Yang et al., 2022; Marín Estañ, 2022).

Model Training and Validation

Training is performed using annotated datasets of dental radiographs, with cross-validation to minimize overfitting.

Performance metrics include identification accuracy, sensitivity, specificity, and model explainability scores, following standards in forensic dental AI applications (Liang et al., 2021; Girijan et al., 2023). Model validation also incorporates simulated forensic scenarios to assess reliability in practical settings.

Explainability and Visualization

To facilitate forensic interpretation, explainability methods such as saliency maps, Grad-CAM, and SHAP are employed to highlight regions of the root canal anatomy that contribute most to model predictions (Yang et al., 2022; Singh, 2022). These visual explanations provide forensic practitioners with a transparent rationale for identification decisions, enhancing trust and legal defensibility.

Ethical Considerations

Data privacy and ethical use are emphasized, ensuring that dental images are anonymized and securely stored, consistent with international forensic research guidelines (Bagde, 2021).

This high-level methodology establishes a structured framework for integrating explainable AI into forensic endodontics, balancing technical rigor with interpretability for practical forensic applications.

Explainability & Validation

Explainable Artificial Intelligence (XAI) is critical in forensic endodontics, where the interpretation of AI outputs must be transparent and defensible in forensic contexts. While conventional deep learning models can achieve high accuracy in identifying root canal patterns, their "black-box" nature limits trust and legal applicability (Singh, 2022; Bagde, 2021). Explainability ensures that decisions, such as linking a root canal morphology to an individual identity, can be interpreted by forensic experts and validated against anatomical knowledge.

Approaches to Explainability

Several XAI strategies have been applied in dental imaging:

Visual explanation techniques

Methods such as Grad-CAM, saliency maps, and attention heatmaps allow the visualization of regions in radiographs that contributed most to the model's decision (Yang et al., 2022). These techniques help forensic odontologists verify that AI focuses on clinically relevant root canal structures rather than irrelevant artifacts.

Model-intrinsic explainability

Decision-tree-based or rule-based approaches provide transparent reasoning paths, making them suitable for high-stakes forensic scenarios (Singh, 2022).

Post-hoc interpretation

Methods like SHAP (SHapley Additive exPlanations) and LIME (Local Interpretable Model-agnostic Explanations) assign importance scores to extracted dental features, allowing the identification of which aspects of the root canal pattern were decisive for identification (Liang et al., 2021; 최혜란, 2022).

Validation of Explainable Models

Validation in forensic endodontics must assess both accuracy and reliability of explanation. Several studies have demonstrated the robustness of AI in recognizing root canal morphologies across different populations and imaging modalities (Girijan et al., 2023; Marín Estañ, 2022). Yang et al. (2022) specifically validated a deep learning model for classifying C-shaped canals, showing that visual explanations aligned closely with expert annotation.

A comparative overview of validation metrics used in forensic dental AI studies is summarized in Table 1.

Implications for Forensic Practice

Explainable models bridge the gap between AI predictions and forensic interpretation. They enable:

- Verification of AI outputs by experts
- Documentation of AI reasoning for legal admissibility.
- Identification of model limitations, such as sensitivity to poor image quality or anatomical variation (Singh, 2022; Bagde, 2021).

Thus, integrating explainable AI into forensic endodontics enhances both accuracy and trustworthiness, ensuring that root canal pattern recognition can be reliably used for individual identification.

Implications and Challenges

The integration of explainable AI (XAI) models into forensic endodontics offers transformative potential for human identification based on dental patterns. Root canal morphology is highly individualistic, making it a robust biometric for forensic applications (Girijan et al., 2023). XAI models allow not only automated identification but also transparency in decision-making, which is critical for legal admissibility and forensic accountability (Yang et al., 2022; Singh, 2022).

Forensic Implications

Enhanced Accuracy

Deep learning models trained on panoramic radiographs or CBCT scans can distinguish subtle root canal variations,

Table 1: Validation Metrics and Explainability Approaches in Forensic Dental AI

Study	*Imaging Modality*	*Model Type*	*Accuracy*	*Explainability method*	*Key Findings*
Yang et al., 2022	Periapical & Panoramic X-ray	CNN (Visual Explanation)	94.1%	Grad-CAM, Saliency maps	Heatmaps corresponded to expert-annotated C-shaped canals
Liang et al., 2021	Panoramic X-ray	Deep CNN	91.3%	SHAP, Feature importance	AI identified individual teeth patterns with high reliability
최혜란, 2022	Panoramic X-ray	CNN	92.0%	Grad-CAM	Automated system for individual identification; explanations focused on molar and premolar morphology
Marín Estañ, 2022	Panoramic X-ray	CNN + Attention	93.5%	Attention visualization	High consistency in teeth segmentation and identification
Girijan et al., 2023	Multi-source radiographs	Meta-analysis	88–95%	N/A	Confirmed radiographic diversity requires explainable AI for reliable forensic use
Haghaniifar, 2022	Panoramic X-ray	U-Net for teeth extraction	90.7%	Overlay visualization	Effective preprocessing for downstream forensic identification

Table 2

Challenge category	*Description*	*Impact on forensic practice*	*Reference*
Data Availability	Limited high-quality dental imaging datasets, particularly for rare root canal morphologies.	Hinders model training, potentially reducing identification accuracy.	Girijan et al., 2023; Bagde, 2021
Model Bias & Generalization	AI models may overfit to specific populations or imaging modalities.	Risk of misidentification in diverse forensic cases.	Singh, 2022; Haghanifar, 2022
Explainability Limitations	Current XAI methods may oversimplify complex decisions or fail to capture anatomical nuances.	Forensic credibility may be questioned in court settings.	Yang et al., 2022
Ethical & Privacy Concerns	Storing and processing personal dental records poses data protection challenges.	Requires strict compliance with privacy regulations.	최혜란, 2022; Marín Estañ, 2022
Integration with Existing Forensic Systems	Lack of standardized protocols for dental AI deployment.	May limit practical adoption in forensic workflows.	Liang et al., 2021; Bagde, 2021
Technical Infrastructure	High-resolution imaging and computational resources needed for deep learning models.	May be a barrier in low-resource forensic labs.	Haghanifar, 2022; Singh, 2022

improving identification precision (Liang et al., 2021; 최혜란, 2022).

Explainability

Tools like saliency maps, LIME, and SHAP provide interpretable visualizations of AI decision rationale, ensuring that the forensic reasoning can be reviewed and verified by experts (Yang et al., 2022).

Scalability

AI-based systems enable rapid matching of large dental databases, which is especially useful in mass disaster scenarios or in regions with high population density (Marín Estañ, 2022).

Key Challenges

Despite its promise, the deployment of XAI in forensic endodontics faces several technical, legal, and ethical challenges, summarized in Table 2.

Future Directions

Database Expansion

Collaborative efforts are needed to create comprehensive and ethically managed dental image repositories (최혜란, 2022).

Hybrid Models

Combining AI with traditional forensic methods can increase reliability while maintaining explainability (Yang et al., 2022).

Regulatory Frameworks

Establishing standardized guidelines for AI-based dental identification will ensure forensic admissibility and ethical compliance (Bagde, 2021).

While XAI models present a significant advancement for forensic endodontics, careful attention to data quality, model transparency, legal requirements, and ethical considerations is essential for their safe and effective application. Addressing these challenges will enable robust, interpretable, and scalable AI-assisted human identification based on root canal morphology.

CONCLUSION

The integration of explainable artificial intelligence (XAI) into forensic endodontics represents a transformative approach for linking root canal patterns to individual dental identity. By leveraging deep learning and advanced image analysis, AI models can capture subtle anatomical variations in root canal morphology, which are highly distinctive and resilient markers for human identification (Girijan et al., 2023; Liang et al., 2021). Importantly, the adoption of explainable models ensures that the decision-making process is interpretable and transparent, addressing critical forensic requirements for evidentiary reliability and traceability (Yang et al., 2022; Singh, 2022).

Recent advances demonstrate that convolutional neural networks and other deep learning architectures can efficiently process panoramic and periapical radiographs, automatically extracting root canal features while maintaining high identification accuracy (최혜란, 2022; Marín Estañ, 2022; Haghanifar, 2022). Such AI-driven systems not only enhance the speed and precision of dental identification but also provide visual explanations of the features contributing to each classification, thereby supporting expert validation in forensic contexts (Bagde, 2021; Yang et al., 2022).

Despite these promising developments, challenges remain in standardizing radiographic datasets, accounting for anatomical variability across populations, and ensuring ethical deployment of AI in forensic practice (Girijan et al., 2023; Singh, 2022). Continued research and validation are necessary to refine model robustness, expand cross-population applicability, and integrate AI tools seamlessly into forensic workflows.

In summary, explainable AI models hold significant potential to revolutionize forensic endodontics by providing accurate, transparent, and reproducible methods for human identification based on root canal morphology. Their implementation could establish a new standard for precision, reliability, and accountability in forensic dental practice (Liang et al., 2021; Yang et al., 2022).

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