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Digital Convergence in Dentistry: AI, IoT, and Cybersecurity Management

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Abstract

The integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies into dentistry is revolutionizing clinical diagnostics, treatment planning, patient monitoring, and practice management. However, this digital transformation introduces significant cybersecurity vulnerabilities that must be addressed to ensure patient safety and data privacy. This paper provides a comprehensive review of current AI and IoT applications in dentistry, including diagnostic imaging systems, smart dental devices, and tele-dentistry platforms. We analyze the cybersecurity threat landscape specific to dental informatics, examining risks such as data breaches, ransomware attacks, and medical device hijacking. Furthermore, we propose a multi-layered cybersecurity management framework incorporating blockchain technology, federated learning, and zero-trust architectures tailored to dental practice environments. Finally, we discuss regulatory compliance requirements including HIPAA and GDPR, and present recommendations for dental practitioners to implement secure, AI-driven digital workflows. This review synthesizes findings from 146 peer-reviewed articles and 18 technology platforms published between 2020 and 2025, providing a roadmap for responsible technological adoption in dentistry.

Keywords: Artificial intelligence, Internet of things, Dental informatics, Cybersecurity, IoMT, Digital dentistry, Federated learning, Blockchain.

1. Introduction

Dentistry is undergoing a profound digital transformation driven by emerging technologies such as Artificial Intelligence (AI), Internet of Things (IoT), Digital Twins (DTs), and Large Language Models (LLMs). These advancements offer new paradigms in clinical diagnostics, patient monitoring, treatment planning, and medical education. The concept of "Dentistry 4.0" has emerged, reflecting the integration of digital technologies that were accelerated during the COVID-19 pandemic, including tele-dentistry and remote patient monitoring systems [1-24].

AI applications in dentistry have demonstrated remarkable potential, with machine learning algorithms achieving diagnostic accuracy comparable to or exceeding that of experienced clinicians in controlled settings. Deep learning models, particularly convolutional neural networks (CNNs), have been successfully deployed for caries detection, tooth segmentation, cephalometric analysis, and oral lesion classification. Concurrently, IoT devices ranging from smart toothbrushes to intraoral sensors are enabling continuous patient monitoring and data collection, creating opportunities for personalized preventive care and remote treatment supervision [25-45].

1.2 The Security Imperative

However, this digital convergence introduces critical cybersecurity challenges that cannot be overlooked. The healthcare sector has become a prime target for cybercriminals, with dental practices increasingly facing ransomware attacks, data breaches, and medical device vulnerabilities. A 2023 survey indicated that over 60% of dental practices had experienced some form of cyber incident, yet many lacked adequate security infrastructure [46-70].

The interconnected nature of AI and IoT systems creates an expanded attack surface. Smart dental devices collect sensitive patient data, AI algorithms require access to large datasets for training, and cloud-based practice management systems store protected health information (PHI). Each of these components represents a potential entry point for malicious actors.

1.3 Scope and Objectives

This paper aims to:
1. Review current AI and IoT applications in dental practice
2. Analyze cybersecurity threats specific to dental informatics
3. Evaluate existing security frameworks and their applicability to dentistry
4. Propose an integrated cybersecurity management model for AI-

IoT dental systems
5. Provide practical recommendations for dental practitioners and technology developers

1.4 Methodology
This review synthesizes findings from a comprehensive literature search conducted across PubMed, IEEE Xplore, and SpringerLink, targeting publications from 2020 to 2025. The final selection included 146 peer-reviewed articles and 18 commercial technology platforms, categorized by technology domain, application type, evaluation metrics, and security considerations.

2. Artificial Intelligence in Dentistry: Current Applications
2.1 Diagnostic Imaging and Analysis
AI has emerged as a cornerstone technology in dental diagnostics, particularly in radiographic image analysis. Deep learning algorithms, especially convolutional neural networks (CNNs), have demonstrated exceptional performance across multiple diagnostic tasks.

Caries Detection: Multiple studies have reported AI models achieving accuracy exceeding 90% in detecting dental caries from bitewing and panoramic radiographs. A systematic review and meta-analysis established strong evidence for machine learning applications in caries detection, with some models achieving sensitivity and specificity comparable to senior radiologists [71-90].

Tooth Segmentation and Classification: U-Net convolutional networks have achieved 96.2% accuracy in automatic tooth segmentation from periapical X-rays. Advanced architectures including YOLOv4 and EfficientNetV2 have been successfully employed for cephalometric landmark detection, while MobileNetV2 combined with Explainable AI (XAI) provides transparent diagnostic reasoning.

Periodontal Assessment: AI-assisted diagnostic tools, such as Planmeca Romexis, have demonstrated diagnostic consistency comparable to senior dental practitioners in detecting alveolar bone loss and periodontal pockets, showcasing significant clinical value in periodontal assessments.

Oral Lesion Detection: DenseNet121 achieved 99% accuracy and F1-score for oral lesion classification, representing a significant advancement in early detection of potentially malignant disorders.

2.2 Treatment Planning and Personalized Care
AI is increasingly assisting clinicians with complex treatment planning decisions across multiple dental specialties.

Orthodontics: Neural network models have achieved 93% accuracy for extraction decisions and 89% for extraction pattern selection in orthodontic treatment planning. AI-driven software optimizes aligner design and treatment timelines, enabling personalized orthodontic care.

Implantology: Traditional CNN-based models evaluate periodontal conditions and simulate implant positions in Cone-Beam Computed Tomography (CBCT) scans with high spatial precision, enhancing treatment planning fidelity.

Prosthodontics: CAD/CAM systems integrated with AI algorithms assist in designing crowns, bridges, and removable prostheses with unprecedented accuracy. AI-driven workflows optimize material selection, restoration geometry, and occlusal morphology based on functional and biomechanical requirements [91-103].

2.3 Practice Management and Patient Communication
Beyond clinical applications, AI is transforming dental practice operations through automation and enhanced patient engagement.

Administrative Automation: Natural Language Processing (NLP) and chatbot models streamline operations including patient scheduling, insurance verification, and query resolution. AI agents can handle insurance verification, claims creation, denial management, and payment posting, potentially saving over 160 work hours per month per practice [104-121].

Revenue Cycle Management: AI-powered billing tools, such as those developed by Overjet and Hathr.AI, reduce coding errors by up to 85% and accelerate claim processing by 90%, significantly improving practice revenue cycles while maintaining HIPAA compliance.

Patient Communication: Interactive AI-powered visualizations simulate treatment outcomes, enhancing informed consent and patient engagement. Large Language Models (LLMs) are being deployed for patient education, post-operative instruction, and remote follow-up.

2.4 Challenges in AI Implementation
Despite promising results, significant barriers to AI adoption in dentistry persist. Studies have identified methodological gaps in evaluation design, insufficient sample sizes, and lack of real-world validation for many AI systems. Additionally, algorithmic bias, regulatory uncertainty, and clinician skepticism remain obstacles to widespread implementation [122-140].

3. Internet of Things in Dentistry
3.1 Smart Dental Devices
The Internet of Dental Things (IoDT) represents an emerging paradigm in oral healthcare, enabling continuous monitoring and data-driven interventions.

Smart Toothbrushes: IoT-enabled toothbrushes equipped with sensors for pressure, motion, and halitosis detection provide real-time feedback on brushing technique. Recurrent probabilistic neural networks (RPNN) have demonstrated 99.08% accuracy in toothbrush posture recognition, enabling personalized oral hygiene instruction.

Intraoral Sensors: Miniaturized sensors capable of monitoring pH, temperature, and bacterial activity provide continuous data on oral health status, enabling early intervention for caries and periodontal disease.

Wearable Devices: Integration of dental IoT data with general health wearables creates opportunities for holistic health monitoring, recognizing the established links between oral health and systemic conditions including cardiovascular disease and diabetes.

3.2 Remote Monitoring and Tele-dentistry

IoT infrastructure enables remote patient monitoring and virtual care delivery, particularly valuable for follow-up care, orthodontic supervision, and management of chronic oral conditions.

Orthodontic Monitoring: AI-assisted analysis of patient-submitted intraoral images enables remote assessment of aligner fit and tooth movement, reducing the need for in-person visits while maintaining treatment oversight[141-150].

Post-operative Surveillance: IoT-connected sensors can monitor healing following surgical procedures, alerting clinicians to signs of infection or complication before they become clinically significant [151-170].

3.3 Current Limitations

A critical finding from recent reviews is that IoT and Digital Twin implementations in dentistry remain largely conceptual or in pilot stages. Unlike AI diagnostics, which have achieved clinical deployment, comprehensive IoT ecosystems in dental practice face significant barriers including cost, interoperability, and security concerns.

4. Cybersecurity Challenges in Dental Informatics

4.1 The Threat Landscape

Dental practices face a range of cybersecurity threats that mirror those in broader healthcare, but with unique characteristics related to practice size, resource constraints, and the specific nature of dental data.

Ransomware Attacks: The healthcare sector has become a primary target for ransomware, with attacks potentially crippling practice operations, encrypting patient records, and threatening data availability. In IoMT environments, ransomware could theoretically disable connected medical devices, creating direct patient safety risks.

Data Breaches: Dental practices maintain extensive repositories of protected health information (PHI), including radiographic images, treatment records, and insurance data. Breaches can result from external attacks, insider threats, or inadequate security controls. The average cost of a healthcare data breach exceeded $10 million in 2023.

Medical Device Hijacking: Connected dental devices including intraoral scanners, CBCT units, and digital radiography systems represent potential entry points for network intrusion. Compromised devices could be used to deliver false diagnostic information, disrupt treatment, or serve as pivots for broader network attacks.

Insider Threats: Dental practices often have high staff turnover and may lack comprehensive access controls. Both malicious and accidental insider actions pose significant risks to data security.

4.2 Vulnerabilities Specific to AI and IoT Systems

The integration of AI and IoT introduces unique security challenges beyond traditional IT systems.

AI-Specific Risks:

- Model poisoning through adversarial inputs
- Data leakage through model outputs
- Lack of explainability impeding security auditing
- Supply chain vulnerabilities in pre-trained models

IoT-Specific Risks:

- Limited computational resources preventing robust encryption
- Default credentials and inadequate patch management
- Network exposure through wireless connectivity
- Physical access vulnerabilities

4.3 Regulatory Compliance Requirements

Dental practices in the United States must comply with HIPAA Privacy, Security, and Breach Notification Rules. Key requirements include:

- Administrative safeguards: risk assessments, workforce training, contingency planning
- Physical safeguards: facility access controls, workstation security, device disposal procedures
- Technical safeguards: access control, audit controls, integrity controls, transmission security
- Business Associate Agreements for third-party AI and cloud vendors

Similar regulations globally include GDPR (Europe), PIPEDA (Canada), and APPI (Japan), each with specific requirements for health data protection and breach notification.

5. Cybersecurity Management Framework for Dental AI-IoT Systems

5.1 Blockchain-Based Security Architecture

Blockchain technology offers promising solutions for addressing data security, integrity, and access control challenges in dental informatics.

Immutable Audit Trails: Blockchain's tamper-proof ledger can record all access to and modifications of patient data, creating verifiable audit trails essential for regulatory compliance and forensic analysis. In dental implantology, blockchain can track the provenance of materials, preventing counterfeit products from entering clinical workflows.

Decentralized Identity Management: Blockchain enables patient-controlled access to health records, allowing individuals to grant and revoke provider access through smart contracts. This aligns with patient autonomy principles and regulatory requirements for data access consent.

Secure Data Sharing: Blockchain-based systems facilitate secure data exchange between dental providers, specialists, and insurance companies without centralized intermediaries that represent single points of failure [171-189].

5.2 Federated Learning for Privacy-Preserving AI

Federated learning (FL) represents a paradigm shift in AI model training that directly addresses privacy concerns in healthcare machine learning.

How FL Works: Instead of aggregating patient data in a central repository, FL brings the AI model to distributed data sources. Each dental clinic trains the model locally on its own patient data, then shares only encrypted model updates (gradients) with a central server. The server aggregates these updates to improve the global model without ever accessing raw patient data.

Applications in Dentistry: A recent study developed a federated learning approach combined with YOLO object detection for automated dental caries detection. Multiple dental establishments trained caries detection models locally, with only model parameters shared with a central server. This approach maintained patient data security and GDPR compliance while achieving model accuracy comparable to centralized training [190-210].

Benefits:
- Patient data never leaves the local institution
- Reduced risk of data breach during transfer
- Compliance with data localization requirements
- Enables collaborative model development across institutions

5.3 Zero-Trust Architecture for Dental Networks

The zero-trust security model assumes no implicit trust for any user or device, regardless of network location. This approach is particularly relevant for dental practices with multiple connected devices and remote access requirements.

Core Principles for Dental Practices:
- Verify every access request regardless of source
- Implement least-privilege access controls
- Assume breach and segment networks accordingly
- Continuous monitoring and validation

Implementation Strategies:
- Micro-segmentation separating clinical devices from administrative networks
- Multi-factor authentication for all system access
- Continuous device posture assessment for IoT endpoints
- Encrypted communication channels for all data transmission

5.4 Intrusion Detection Systems for IoMT

Specialized intrusion detection systems (IDS) designed for medical IoT environments can identify and respond to cyber threats in real-time.

Machine Learning-Based IDS: Recent research has demonstrated the effectiveness of explainable AI (XAI) approaches for cross-layer intrusion detection in IoMT environments. These systems operate on raw packet-level features and application-layer semantics, achieving detection accuracy exceeding 97% while maintaining interpretability for clinical stakeholders.

Key Features:
- Real-time monitoring of device behavior
- Anomaly detection based on expected clinical workflows
- Automated response capabilities for identified threats
- Integration with clinical alerting systems

6. Integration Framework: AI, IoT, and Cybersecurity

6.1 Proposed Architectural Model

Based on our synthesis of current literature and technologies, we propose a multi-layered architecture for secure AI-IoT integration in dental practice (Figure 1).

Layer 1: Device Layer
- IoT sensors and smart dental devices
- Edge computing capabilities for local processing
- Hardware-based security modules
- Regular firmware update mechanisms

Layer 2: Network Layer
- Segmented network design (clinical, administrative, guest)
- Encrypted communication protocols (TLS 1.3, MQTTS)
- Network intrusion detection systems
- Zero-trust network access controls

Layer 3: Data Layer
- Encrypted data storage (AES-256 at rest)
- Blockchain-based audit trails
- Federated learning infrastructure
- Automated backup with off-site replication

Layer 4: Application Layer
- AI diagnostic and planning tools
- Practice management systems
- Patient portals and tele-dentistry platforms
- Role-based access controls

Layer 5: Governance Layer
- Policy management and enforcement
- Compliance monitoring (HIPAA, GDPR)

• Incident response procedures
• Regular security assessments

6.2 Workflow Integration Example

A typical secure clinical workflow incorporating these elements:
1. Patient Check-in: Patient data encrypted and logged to blockchain audit trail
2. Data Collection: IoT sensors collect intraoral data, processed at edge with local encryption
3. AI Analysis: Federated learning model analyzes images without raw data leaving clinic
4. Treatment Planning: AI recommendations presented through secure clinical workstation with MFA
5. Data Storage: All records encrypted, access logged to immutable ledger
6. Billing: AI-powered billing system processes claims through HIPAA-compliant cloud with end-to-end encryption
7. Follow-up: Remote monitoring data transmitted through secure IoT gateway

6.3 Implementation Roadmap

For dental practices seeking to implement secure AI-IoT systems, we recommend a phased approach [211-214]:

Phase 1: Assessment (1-3 months)
• Conduct security risk assessment
• Inventory all connected devices and data flows
• Identify compliance requirements
• Develop security policies

Phase 2: Foundation (3-6 months)
• Implement network segmentation
• Deploy multi-factor authentication
• Establish encryption for data at rest and in transit
• Train staff on security awareness

Phase 3: Integration (6-12 months)
• Pilot AI diagnostic tools with security review
• Implement IoT devices with security-by-design
• Deploy intrusion detection systems
• Establish incident response procedures

Phase 4: Optimization (ongoing)
• Continuous monitoring and improvement
• Regular security assessments
• Update policies based on emerging threats
• Expand AI/IoT capabilities with security validation

7. Ethical and Regulatory Considerations

7.1 Algorithmic Bias and Fairness

AI systems trained on non-representative datasets may perpetuate or amplify existing disparities in oral healthcare. Studies have noted that many dental AI models are trained on datasets lacking diversity in terms of race, ethnicity, socioeconomic status, and geographic representation.

Mitigation Strategies:
• Diverse and representative training datasets
• Regular bias auditing of AI outputs
• Transparency in model limitations
• Human oversight of AI recommendations

7.2 Patient Consent and Autonomy

The collection and analysis of patient data through AI and IoT systems requires informed consent that adequately explains:
• What data will be collected
• How data will be used (including for AI training)
• Who will have access to data
• How patients can withdraw consent
• Data retention and deletion policies

7.3 Professional Liability

The use of AI in clinical decision-making raises questions about professional liability. Current regulatory frameworks generally hold clinicians responsible for final treatment decisions, even when informed by AI recommendations. Documentation of AI use and human oversight is essential for risk management.

7.4 Data Sovereignty and Cross-Border Issues

For dental practices utilizing cloud-based AI services or participating in federated learning networks, data sovereignty concerns arise. Patient data may be subject to regulations of jurisdictions where it is processed or stored, creating compliance complexity for international dental chains or tele-dentistry services.

8. Future Directions

8.1 Digital Twins in Dentistry

Digital Twin (DT) technology virtual replicas of physical dental anatomy or clinic operations represents a promising frontier. DTs could enable:
• Personalized treatment simulation before clinical intervention
• Real-time procedure guidance comparing actual to planned outcomes
• Predictive maintenance of dental equipment
• Risk-free training environments for complex procedures

However, current DT implementations in dentistry remain largely conceptual, with significant technical and security challenges to overcome before clinical deployment.

8.2 Edge AI for Real-Time Processing

Moving AI processing from cloud to edge devices (intraoral cameras, smart brushes, local workstations) offers security and performance benefits:
• Reduced data transmission (minimizing exposure)
• Lower latency for real-time feedback
• Compliance with data localization requirements
• Reduced cloud dependency and associated risks

8.3 Post-Quantum Cryptography

As quantum computing advances, current encryption standards may become vulnerable. The healthcare sector should begin planning for migration to post-quantum cryptographic algorithms, particularly for long-term patient records that must remain confidential for decades.

8.4 Regulatory Evolution

We anticipate continued evolution of regulations governing AI in healthcare, including:

- FDA approval pathways for AI diagnostic devices
- Standards for AI model validation and monitoring
- Requirements for algorithmic transparency and explainability
- Liability frameworks for AI-assisted decisions

9. Recommendations for Stakeholders

9.1 For Dental Practitioners

1. Conduct regular security risk assessments specific to connected devices and AI systems
2. Implement basic security controls including encryption, MFA, and regular backups before adding advanced technologies
3. Require security certifications from AI and IoT vendors (e.g., HITRUST, SOC 2)
4. Develop incident response plans that address both data breaches and device compromise scenarios
5. Invest in staff training on cybersecurity awareness and secure technology use
6. Document AI-assisted decisions including human review and override of AI recommendations

9.2 For Technology Developers

1. Adopt security-by-design principles throughout the development lifecycle
2. Provide transparent documentation of data handling, security controls, and compliance certifications
3. Implement federated learning capabilities to enable collaborative model improvement without data sharing
4. Include explainability features that enable clinical audit of AI decisions
5. Design for interoperability with existing practice management systems using standard APIs

9.3 For Policymakers

1. Develop dental-specific guidance for AI and IoT security, recognizing the unique characteristics of dental practice
2. Support research on security frameworks for healthcare IoT and edge AI
3. Create incentive programs for small dental practices to implement essential security controls
4. Establish reporting mechanisms for AI-related adverse events and security incidents in dental settings

10. Conclusion

The convergence of Artificial Intelligence and Internet of Things technologies in dentistry offers transformative potential for diagnostic accuracy, treatment personalization, practice efficiency, and patient engagement. AI systems have demonstrated remarkable performance in radiographic analysis, treatment planning, and administrative automation, while IoT devices enable continuous monitoring and data-driven preventive care.

However, this digital transformation cannot succeed without robust cybersecurity management. The expanded attack surface created by connected devices, the sensitivity of dental health data, and the potential for patient harm from compromised systems demand systematic attention to security from all stakeholders.

Our review identifies that while AI diagnostic tools have achieved clinical validation and deployment, IoT and Digital Twin implementations remain largely conceptual, and security considerations are frequently mentioned but substantively addressed in only a minority of published works. This represents both a significant gap and an opportunity for future research and development.

The framework proposed in this paper integrating blockchain-based audit trails, federated learning for privacy-preserving AI, zero-trust network architecture, and machine learning-based intrusion detection provides a comprehensive approach to securing the dental practices of tomorrow. Success will require collaboration among clinicians, developers, policymakers, and cybersecurity professionals, all working toward the shared goal of responsible, patient-centered digital transformation in oral healthcare.

As dentistry continues its digital evolution, those practices that prioritize security alongside innovation will be best positioned to realize the benefits of AI and IoT while maintaining patient trust and regulatory compliance. The future of dentistry is undoubtedly digital—but it must also be secure.

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