บทความฟื้นวิชา **Review Article**

แปรงสีฟันอัจฉริยะและผลกระทบต่อสุขภาพช่องปาก (การบูรณาการเทคโนโลยี และการดูแลสุขภาพที่ครอบคลุม)
Smart toothbrushes and their impact on oral health (Technology integration, and inclusive care)

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บทคัดย่อ

บทนำ

โรคทางช่องปากส่งผลกระทบต่อประชากรกว่า 3.5 พันล้านคนทั่วโลก โดยมีผลต่อสุขภาพกาย อารมณ์ และเศรษฐกิจ แปรงสีฟันอัจฉริยะเป็นนวัตกรรมใหม่ที่ช่วยแก้ปัญหาของแปรงสีฟันแบบเดิม และแปรงสีฟันไฟฟ้าแบบทั่วไปด้วยคุณสมบัติของการให้ข้อมูลแบบเรียลไทม์ การเชื่อมต่อแอปพลิเคชัน และการดูแลสุขภาพช่องปากแบบเฉพาะบุคคล ช่วยปรับปรุงสุขอนามัยในช่องปากสำหรับประชากรกลุ่มต่างๆ

วัตถุประสงค์

เพื่อศึกษาการพัฒนาและประสิทธิภาพของแปรงสีฟันอัจฉริยะในการส่งเสริมสุขภาพช่องปาก โดยเน้นผลกระทบต่อกลุ่มประชากรที่หลากหลายและคุณสมบัติทางเทคโนโลยี ประโยชน์ในการกำจัดคราบจุลินทรีย์และดูแลเหงือก รวมถึงความท้าทายและความสามารถของแปรงสีฟันอัจฉริยะในปัจจุบันและศักยภาพในอนาคตเพื่อพัฒนาการดูแลสุขอนามัยในช่องปาก

วิธีการศึกษา

ทบทวนวรรณกรรมแบบ Systematic review และวิเคราะห์การพัฒนาการใช้งานและประสิทธิภาพของแปรงสีฟันอัจฉริยะ โดยคัดเลือกงานวิจัยที่ผ่านการตรวจสอบโดยผู้ทรงคุณวุฒิ ในปี ค.ศ. 2000 - 2024 จาก PubMed, Scopus และ Google Scholar โดยใช้คำค้นหาเช่น "แปรงสีฟันอัจฉริยะ" และ "เทคโนโลยีสุขภาพช่องปาก" งานวิจัยที่ได้รับการคัดเลือกจะต้องศึกษาผลลัพธ์ทางสุขภาพช่องปากในประชากรที่หลากหลาย และมีการตัดบทความที่ไม่ใช่ภาษาอังกฤษหรือไม่มีพื้นฐานทางวิทยาศาสตร์ออก

ผลการศึกษา

แปรงสีฟันอัจฉริยะปรับปรุงเทคนิคการแปรงฟัน ลดคราบจุลินทรีย์ และป้องกันโรคเหงือก มีการใช้เทคโนโลยีปัญญาประดิษฐ์ (AI) เช่น การให้ข้อมูลแบบเรียลไทม์ และอัลกอริทึมการเรียนรู้ของเครื่อง Machine Learning ทำให้การแปรงฟันมีประสิทธิภาพมากขึ้นและช่วยเพิ่มอัตราการขจัดคราบจุลินทรีย์ได้สูงถึง 87% เมื่อเทียบกับแปรงสีฟันทั่วไป นอกจากนี้เครื่องมือแบบอินเทอร์ แอคทีฟ เช่น เทคโนโลยีเสมือนจริง (AR) และเกมมิฟิเคชัน อย่าง Brush Monster ช่วยส่งเสริมพฤติกรรมการดูแลช่องปากในเด็กและบุคคลที่มีความบกพร่องทางสติปัญญาทำให้สามารถแปรงฟันได้อย่างอิสระและลดภาระของผู้ดูแล แปรงสีฟันอัจฉริยที่มีบลูทูธและระบบติดตามข้อมูลผ่านแอปพลิเคชัน ยังช่วยให้การดูแลสุขภาพช่องปากเป็นรายบุคคล โดยเฉพาะในกลุ่มผู้ที่มีภาวะบกพร่องทางสติปัญญาและโรคเรื้อรัง เช่น เบาหวานชนิดที่ 2 นอกจากนี้แปรงสีฟันอัจฉริยะยังช่วยทำความสะอาดอวัยวะเทียมในช่องปาก (Prosthetic cleaning) สำหรับผู้ไร้ฟัน (Edentulous patients) ช่วยส่งเสริมสุขภาพเหงือก และควบคุมระดับน้ำตาลในเลือดสำหรับผู้ป่วยเบาหวาน พบความท้าทายด้านราคาที่สูงและปัญหาด้านความเป็นส่วนตัวของข้อมูล ยังคงเป็นอุปสรรคที่ต้องได้รับการแก้ไข โดยเน้นไปที่นวัตกรรมที่ยั่งยืนและการเข้าถึงที่เท่าเทียมกัน

สรุป

แปรงสีฟันอัจฉริยะเป็นนวัตกรรมที่พัฒนาการดูแลสุขภาพช่องปาก และช่วยปรับปรุงคุณภาพชีวิตของประชากรกลุ่มต่างๆ การนำเทคโนโลยีนี้มาใช้ร่วมกับการพัฒนาทางวิทยาศาสตร์ นโยบายสนับสนุน และการทำงานร่วมกัน ระหว่างสาขาวิชาจะช่วยผลักดันให้การดูแลสุขภาพช่องปากเป็นไปอย่างยั่งยืน และเข้าถึงได้ทั่วโลก

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Abstract

Introduction: Oral diseases affect over 3.5 billion people worldwide, impacting physical, emotional, and economic well-being. Smart toothbrushes are an innovative solution addressing the limitations of traditional manual and electric toothbrushes by offering real-time feedback, mobile application connectivity, and personalized oral health care. These features help improve oral hygiene across different population groups.

Objective: To examine the development and effectiveness of smart toothbrushes in promoting oral health, with a focus on their impact on diverse populations, technological features, benefits in plaque removal and gum care, as well as challenges, this review synthesizes existing research to present a concise overview of smart toothbrushes, their current capabilities, and their future potential in advancing oral hygiene.

Methods: This study conducted a systematic literature review, analyzing the development, application, and effectiveness of smart toothbrushes. Peer-reviewed research (2000-2024) was selected from PubMed, Scopus, and Google Scholar using search terms such as “smart toothbrush” and “oral health technology.” Studies focused on oral health outcomes in diverse populations, while non-English and non-scientific articles were excluded.

Results: Smart toothbrushes improve brushing techniques, reduce plaque, and help prevent gum diseases. They utilize artificial intelligence (AI) technologies such as real-time feedback and machine learning algorithms, enhancing brushing efficiency and increasing plaque removal rates by up to 87% compared to traditional toothbrushes. Interactive tools, including augmented reality (AR) and gamification (e.g., Brush Monster), promote oral hygiene behaviors in children and individuals with intellectual disabilities, allowing for greater independence and reducing caregiver burden. Bluetooth connectivity and app-based data tracking enable personalized oral health care, especially benefiting individuals with cognitive impairments and chronic conditions like Type 2 diabetes. Additionally, smart toothbrushes improve the cleaning of oral prosthetics for edentulous patients and support gum health while aiding glycemic control in diabetic patients. However, challenges such as high costs and privacy concerns remain obstacles that need to be addressed, emphasizing the need for sustainable innovation and equitable access.

Conclusion: Smart toothbrushes are an innovation that enhances oral health care and improves the quality of life for different population groups. Integrating this technology with scientific advancements and supportive policies can drive accessibility, sustainability, and equitable oral health care.

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Introduction

Oral health problems remain a significant global burden, affecting approximately 3.5 billion people worldwide. Common conditions such as untreated dental caries, periodontal disease, tooth loss (edentulism), and oral cancers not only impact physical health but also emotional well-being, and overall quality of life. Nearly 2.4 billion people suffer from cavities in their permanent teeth, while over a billion experience severe gum disease, contributing to pain, infection, and potential tooth loss[(1)]. The World Health Organization (WHO) reports that the prevalence of oral diseases has increased by more than 50% between 1990 and 2019, outpacing population growth and highlighting the inadequacy of current preventive measures[(2)].

The burden of oral diseases disproportionately affects low- and middle-income countries, where three out of four cases occur. Socioeconomic disparities, lack of education, and limited access to dental care exacerbate the issue. In many marginalized communities, particularly in rural areas, oral healthcare remains difficult to access due to the concentration of dental services in urban centers and the exclusion of oral health from primary healthcare systems[(2)]. Additionally, in regions where healthcare is privatized, high treatment costs further limit access, widening health inequalities.

Beyond physical consequences, oral diseases negatively impact daily life, causing pain, difficulty in eating, and impaired speech. Tooth loss can lead to low self-esteem, social withdrawal, and employment challenges. In children, dental problems can hinder growth, learning, and school attendance, while in adults, poor oral health can result in lost productivity and financial strain. Addressing these issues requires innovative approaches that prioritize prevention and accessibility. Oral diseases share common risk factors with other non-communicable diseases, such as excessive sugar consumption, smoking, and alcohol use[(1)]. Moreover, the aggressive marketing of sugary foods and beverages exacerbates the problem, particularly in low-income communities.

To combat these issues, strengthening public health policies, expanding access to dental care, and leveraging emerging technologies are essential. One promising advancement is the development of smart toothbrushes, which integrate artificial intelligence (Al) and other digital tools to improve oral hygiene. These devices offer personalized guidance, encourage better brushing habits, and make preventive care more accessible to diverse populations. By incorporating real-time feedback, gamification, and data-driven insights, smart toothbrushes represent a modern approach to addressing the global oral health crisis.

History of dental hygiene tools reflects humanity's continuous efforts to improve oral care. Early civilizations relied on natural materials, such as neem twigs in India [(3)] and miswak twigs in the Middle East, both of which possessed antibacterial properties beneficial for oral health[(3)]. The first bristle toothbrush, made from animal hair, was invented in China in the 1400s, later evolving into nylon-bristled toothbrushes in the 1930s, which offered greater durability and hygiene[(3)]. The 1960s marked a major advancement with the introduction of electric toothbrushes, which

improved plaque removal, particularly for individuals with limited dexterity[3]. Subsequent innovations incorporated sonic and ultrasonic technology, further enhancing cleaning efficiency. Recent developments have introduced solar-powered and laser toothbrushes for chemical-free cleaning, as well as eco-friendly bamboo toothbrushes to reduce plastic waste. In addition to toothbrushes, interdental cleaning tools such as dental floss, interdental brushes, and water flossers have been developed to enhance oral hygiene. As technology continues to evolve, the integration of artificial intelligence (AI), augmented reality (AR), and smart sensors in oral care tools represents the next frontier in dental health[3].

Smart toothbrushes represent a groundbreaking advancement in oral hygiene by leveraging digital technology to enhance brushing techniques, provide real-time feedback, and promote better oral care habits. The transition from traditional electric toothbrushes to AI-powered smart toothbrushes has been driven by the growing recognition of oral health's importance in overall well-being. By 2016, the electric toothbrush market had reached a valuation of $2.2 billion, reflecting increasing consumer demand for advanced oral care solutions. Unlike manual and standard electric toothbrushes, intelligent toothbrushes incorporate AI-driven features, app-based tracking, and interactive brushing modes to optimize oral hygiene. These devices help users build better habits by detecting improper brushing techniques, ensuring thorough plaque removal, and offering personalized recommendations[4]. Such innovations are particularly beneficial for vulnerable populations, including children, individuals with disabilities, and older adults, who may require additional guidance and motivation to maintain proper oral hygiene. By combining technology with preventive healthcare, AI-powered toothbrushes have the potential to revolutionize dental hygiene practices, making oral care more engaging, efficient, and accessible. This review explores the impact of smart toothbrush technology on oral health, evaluates its advantages and challenges, and discusses its role in shaping the future of dental care[3].

This literature review aims to systematically analyze the development, functionality, and effectiveness of smart toothbrush technology in improving oral health. Specifically, it examines how they enhance plaque removal, promote gum health, and addresse the needs of diverse populations, including children, individuals with disabilities, and older adults with cognitive impairments. The review also identifies challenges associated with intelligent toothbrush adoption, such as environmental impact, cost barriers, and data privacy concerns. By synthesizing existing scientific studies, this paper provides an overview of the current capabilities of smart toothbrushes, their potential to transform oral care, and areas that require further research and development.

Methodology

This review utilized a systematic approach to analyze the development, application, and effectiveness of smart toothbrushes in oral health. Relevant studies from databases such as PubMed, Scopus, and Google Scholar (2000 - 2024) were identified using keywords like "smart toothbrush" and "oral health technology". Inclusion criteria focused on peer-reviewed

studies evaluating the impact of smart toothbrushes on oral health outcomes across diverse populations, while non-English and non-scientific articles were excluded.

Data on technological features, efficacy in plaque removal and gum health, benefits for vulnerable populations, and challenges (e.g., environmental and privacy concerns) were extracted. Findings were synthesized thematically, and quality was assessed using standardized evaluation tools to ensure reliability and relevance.

Study results

Current Application: Who Uses Smart Toothbrushes

Smart toothbrushes are used by a diverse range of individuals, including children, adults, and those with developmental or cognitive challenges. For children, these devices improve brushing habits and allow parents to monitor oral hygiene, fostering independence[6,9,16,17]. They are also particularly useful for individuals with autism spectrum disorder (ASD), dementia, or mild cognitive impairment (MCI), as they simplify oral care routines and provide structured guidance to make daily brushing more manageable[8,10,11,17].

Beyond these groups, smart toothbrushes also assist adults with type 2 diabetes, periodontal disease, or dentures by helping them maintain oral hygiene and reducing complications associated with poor dental care[14,19,20]. In intensive care units (ICUs), where poor oral health increases the risk of ventilator-associated pneumonia (VAP) due to bacterial accumulation, AI-enabled smart toothbrushes assist healthcare providers by ensuring thorough brushing, minimizing gum damage, and lowering the risk of infections.

Integrating smart toothbrushes into ICU protocols could significantly improve oral hygiene standards and patient outcomes[5]. Overall, smart toothbrushes cater to various populations by offering personalized and adaptive oral care solutions that enhance hygiene practices, improve accessibility, and support individuals with specific needs.

Technological Innovations in Smart Toothbrushes: AI, ML, DL

AI-powered smart toothbrushes utilize machine learning (ML) and deep learning (DL) algorithms to enhance brushing efficiency, detect errors, and provide real-time feedback. The Massachusetts Institute of Technology (MIT) defines AI as a system enabling machines to perform tasks that typically require human intelligence. ML, a subset of AI, improves performance over time by analyzing user behavior and brushing patterns. DL, which operates on larger datasets and neural networks, powers advanced applications like speech and image recognition in oral health tools. For applications in Oral Health a study conducted by Yang et al. (2024) tested an AI-driven smart toothbrush that analyzed sensor data to provide personalized guidance through music, animations, and brushing tutorials on smartphones[6]. Children in the AI-assisted group showed significantly better plaque reduction than those using conventional brushing methods ($p < 0.05$)[6]. Chen et al. (2021) introduced a recurrent probabilistic neural network (RPNN) to recognize toothbrush posture, achieving 99.08% accuracy, surpassing other models like CNNs and LSTMs[7]. This AI-driven system enhances brushing efficiency and ensures effective plaque removal while being compatible with

low-power smartphones[7]. These findings highlight how AI-powered smart toothbrushes are revolutionizing oral hygiene by providing data-driven, interactive, and highly accurate guidance.

3D and Augmented Reality (AR) Features in Smart Toothbrushes

3D visualization and augmented reality (AR) have transformed oral health education by making brushing more interactive and engaging. Augmented reality overlays digital instructions onto the real-world environment, guiding users step-by-step to ensure effective brushing. For Key Applications, Jeon et al. (2021) studied the Brush Monster, an AR-integrated toothbrush that visually demonstrates correct brushing techniques on a smartphone screen[8]. Users received real-time brushing feedback, significantly improving oral hygiene among individuals with intellectual disabilities[8]. Kim et al. (2009) developed a motion-sensing toothbrush that displayed 3D animations of optimal brushing techniques. Children who used this system exhibited higher engagement and improved brushing accuracy, reinforcing proper oral care habits[9]. By combining gamification, visual learning, and real-time monitoring, these innovations make brushing more effective and enjoyable, particularly for children and individuals with cognitive impairments.

Smart Toothbrush Innovations for Individuals with Dementia

Dementia affects cognitive function, memory, and daily activities, often leading to neglected oral hygiene. To address this, researchers have developed AI-assisted smart toothbrushes equipped with laser sensors, motion tracking, and Bluetooth connectivity to guide users step-by-step. Shakeri Jannati et al. (2023) introduced an intelligent toothbrush designed for dementia patients, incorporating RGB LED indicators, a 9-axis motion sensor, and audio guidance via a smartphone app[10]. The device assists users in completing a 25-step brushing routine, ensuring all quadrants of the mouth are cleaned[10]. Early trials demonstrated enhanced brushing autonomy, better oral hygiene, and reduced caregiver burden[10]. This technology represents a significant advancement in assistive oral care, enabling independent brushing and reducing reliance on caregivers.

Bluetooth-Enabled Smart Toothbrushes

Bluetooth technology plays a vital role in connecting smart toothbrushes to mobile apps, enabling real-time tracking and feedback. Bluetooth Low Energy (BLE) ensures continuous data transmission without excessive battery consumption. Shakeri Jannati (2020) demonstrated that Bluetooth-enabled smart toothbrushes monitored brushing progress, provided step-by-step guidance, and helped users develop better habits[10]. Humm et al. (2020) found that AI-powered toothbrushes improved plaque reduction and brushing duration by giving users personalized feedback through connected apps[11]. For individuals with cognitive impairments, Bluetooth technology enhances independence and oral hygiene adherence, making brushing more structured and effective.

Benefits of Smart Toothbrushes

Proper brushing technique is essential for preventing cavities, gum disease, and plaque buildup. The National Institute on Aging (NIA) emphasizes brushing twice daily with fluoride toothpaste

to maintain oral health. Smart toothbrushes improve brushing outcomes by providing real-time feedback on technique, pressure, and brushing duration, guiding users to reach neglected areas, such as molars and gum lines and motivating longer brushing sessions through interactive features. Jeong et al. (2022) found that children using a Smart Mirror Toothbrush (STM) system reduced plaque by 40.50%, comparable to those receiving traditional brushing instruction[16]. Yang et al. (2024) reported that AI-powered toothbrushes reduced plaque scores from 1.41 to 0.98, demonstrating superior efficacy compared to manual brushing[6]. These studies confirm that smart toothbrushes significantly enhance oral hygiene practices across various populations.

Comparing Smart and Electric Toothbrushes vs. Manual Toothbrushes

Smart toothbrushes have consistently outperformed manual toothbrushes in plaque removal and gum health improvement. A study conducted by Walters et al. (2007) reported that the Oral-B Triumph smart toothbrush removed 87% of plaque, compared to 70% with manual brushing[12]. Alkilzy et al. (2019) found that app-connected toothbrushes reduced plaque scores from 2.36 to 0.44 over 12 weeks[13]. Humm et al. (2020) showed an 8.5% improvement in plaque reduction among users of smart toothbrushes, compared to 4.7% with manual toothbrushes[11]. These findings highlight the superior efficacy of smart toothbrushes in achieving comprehensive oral hygiene.

Smart Toothbrushes and Periodontal Health

Gingivitis and periodontitis are chronic inflammatory conditions that can lead to tooth loss and systemic health issues. Previous studies by Adam (2020) found that 82% of Oral-B iO smart toothbrush users had "healthy" gums, compared to 24% of manual toothbrush users[14]. And Janusz et al. (2008) demonstrated that smart toothbrushes reduced excessive brushing pressure by 88.5%, preventing gum recession and damage[15]. These features make intelligent toothbrushes highly effective in reducing gingival inflammation and preventing periodontal disease. Ai-powered toothbrushes integrate AI, AR, and Bluetooth to enhance brushing efficiency, engagement, and accessibility for diverse populations. They significantly improve plaque removal, brushing habits, and gum health, making them ideal for children, individuals with disabilities, and those with chronic conditions. As technology advances, smart toothbrushes will continue reshaping oral health practices, promoting preventive care, and improving accessibility worldwide.

Challenges and Limitations

The environmental impact of smart (electric) toothbrushes compared to manual toothbrushes presents a significant sustainability challenge. Research by Shah et al. (2020) and Lyne et al. (2020) indicates that electric toothbrushes contribute to greater environmental harm in 15 out of 16 studied areas, including climate change, land degradation, and biodiversity loss[21,22]. The primary reasons behind this impact include the use of non-renewable materials, such as plastics, metals, and lithium-ion batteries, as well as the high energy consumption required for their production. Additionally, electric toothbrushes pose challenges in disposal and recycling due to their complex mix of components, making

them a significant contributor to electronic waste[21]. Their transportation also results in higher carbon emissions, further increasing their ecological footprint. In contrast, manual toothbrushes, particularly those with bamboo handles or replaceable heads, offer a more sustainable alternative. Bamboo toothbrushes are biodegradable, while replaceable-head toothbrushes reduce plastic waste, significantly lowering their environmental impact[22]. Despite the superior cleaning efficiency and technological advantages of electric toothbrushes, their environmental cost remains a concern. Manufacturers must explore eco-friendly innovations, such as biodegradable electronic components and recyclable batteries, to mitigate their negative impact on the planet.

Despite their technological advancements, smart toothbrushes risk widening health disparities, particularly in low-income communities and underserved populations. According to Johan Flyborg (2024), affordability remains a major barrier, as these toothbrushes are significantly more expensive than manual alternatives. Many models also require ongoing costs, such as app subscriptions and internet connectivity, making them inaccessible to those with limited financial resources[18].

Another critical issue is the digital divide, where individuals in regions with poor internet connectivity or low digital literacy struggle to use smart toothbrush features effectively. In areas where real-time AI feedback and health monitoring are unavailable due to infrastructure limitations, the core benefits of smart toothbrushes are lost. In Sweden, for example, only 20.3% of individuals over 85 years old use digital tools, making intelligent toothbrush adoption impractical for many seniors. This challenge is even more pronounced in developing countries, where a lack of digital literacy and stable internet access further limits adoption[18]. Flyborg describes these barriers as an “invisible line” that separates individuals who can benefit from smart toothbrush technology from those who cannot. Without efforts to lower costs, improve accessibility, and simplify technology usage, smart toothbrushes may unintentionally widen oral health inequalities rather than bridging them. Addressing this issue will require affordable pricing models, offline functionality, and user-friendly designs to ensure that smart toothbrushes can serve diverse populations, including those most in need of improved oral healthcare.

The increasing reliance on AI and data collection in smart toothbrushes has raised significant concerns about user privacy and data security. These devices gather detailed brushing behavior data, including brushing frequency, pressure, technique, and oral health conditions. While this data allows for personalized feedback and AI-driven oral care recommendations, it also introduces the risk of misuse and unauthorized access. To address these concerns, companies like Philips adhere to General Data Protection Regulation (GDPR) guidelines, which ensure that users are informed about what data is collected, how it is stored, and who has access to it. GDPR also grants users the right to access, modify, and delete their personal data while requiring companies to obtain explicit consent before data collection. Despite these regulations, concerns persist regarding data transparency and third-party sharing, particularly when smart toothbrush data is linked to insurance providers, social media accounts, or other digital platforms. Additionally, the integration of artificial intelligence

(AI) and machine learning in smart toothbrushes complicates privacy risks, as users may not fully understand how much data is being analyzed or how AI-generated insights influence oral health recommendations. Reports from technology watchdogs like Ars Technica have highlighted potential security vulnerabilities, but the lack of extensive scientific research on smart toothbrush data protection leaves many questions unanswered. Moving forward, stronger encryption methods, enhanced user consent mechanisms, and increased regulatory oversight will be crucial to ensuring data privacy and building consumer trust in AI-powered oral health technologies.

Future Directions and Innovations

The next generation of smart toothbrushes is expected to extend beyond basic oral hygiene, integrating biometric tracking and health diagnostics to monitor overall well-being. For example, Yoshimura et al. (2021) developed a breath-analysis toothbrush equipped with odor, moisture, and pressure sensors that can detect halitosis (bad breath) while also assessing biomarkers linked to stress levels and mental health[23]. This technology could pave the way for toothbrushes that monitor physiological indicators, offering insights into a user's stress, hydration, or even early signs of disease.

Another breakthrough is the LumiO smart toothbrush, which utilizes blue-violet light to highlight plaque buildup in real-time. By integrating machine learning algorithms, LumiO not only visualizes plaque accumulation but also provides personalized brushing recommendations, guiding users on how to improve their technique[24]. Future iterations of these toothbrushes may include thermal imaging for detecting gum inflammation, salivary diagnostics for tracking hydration and pH

In addition to diagnostic capabilities, future smart toothbrushes are likely to feature AI-powered health monitoring tools that analyze oral pH levels, saliva composition, and glucose levels-potentially aiding in early detection of diseases such as diabetes and gastrointestinal conditions. Advances in haptic feedback and pressure sensors will further refine brushing pressure guidance, reducing the risk of gum damage and enamel wear.

To address environmental concerns, manufacturers are developing sustainable toothbrush designs, including biodegradable plastics, recyclable battery components, and energy-efficient motors. Some companies are exploring the use of wireless charging through solar energy or kinetic energy conversion, reducing reliance on disposable batteries.

Additionally, smart toothbrushes could play a larger role in preventive healthcare programs by integrating with corporate wellness initiatives and insurance-based dental monitoring programs. Employers and healthcare providers may leverage this technology to encourage better oral hygiene practices, potentially linking brushing habits to insurance premium discounts or workplace health incentives.

As smart toothbrush technology continues to evolve, its potential impact extends beyond oral health into holistic health monitoring and preventive care. While these innovations promise enhanced brushing effectiveness, disease detection, and interactive user experiences, challenges related to privacy, accessibility, and environmental sustainability must

be addressed. Efforts to reduce costs, improve digital inclusivity, strengthen data protection, and adopt eco-friendly materials will be essential in ensuring that smart toothbrushes benefit a broader population. As these devices advance, they could revolutionize not only dental care but also contribute to early disease detection, mental health tracking, and overall wellness monitoring-transforming the simple act of brushing into a powerful health tool for the future.

Discussion

Smart toothbrushes have demonstrated significant potential in improving oral hygiene, brushing techniques, and personalized dental care for a wide range of users. Research consistently shows that intelligent toothbrushes outperform manual toothbrushes in plaque removal and gum health improvement due to their advanced features, such as oscillating-rotating technology, pressure sensors, and real-time feedback mechanisms. These innovations are particularly beneficial for individuals who struggle with proper brushing techniques, as they help reduce gum inflammation and enhance oral hygiene habits[12,14]. Additionally, the integration of AI and app-based guidance provides personalized feedback, making brushing more engaging, especially for children and individuals with developmental disabilities[13,16]. However, despite these advantages, several challenges must be addressed to maximize the benefits of AI-powered toothbrushes. One of the most significant benefits of smart toothbrushes is their role in habit formation and behavioral change. Studies indicate that children using smart toothbrushes with gamification elements and 3D visuals exhibit higher motivation to brush, leading to long-term improvements in plaque control and overall oral health[16]. Similarly, for individuals with cognitive impairments such as dementia, smart toothbrushes provide structured guidance through step-by-step instructions, promoting independent brushing and reducing caregiver burden[16]. While these features enhance accessibility, a technological gap remains among older adults and individuals unfamiliar with digital tools, limiting adoption among seniors and those with limited experience using smartphone apps[10,18]. Efforts should be made to simplify user interfaces, provide voice-guided instructions, and integrate offline functionality to ensure inclusivity. Despite their health benefits, intelligent toothbrushes pose environmental and economic challenges. Their production involves electronic components, lithium-ion batteries, and plastic materials, resulting in a higher environmental footprint compared to manual toothbrushes[21,22]. While some manufacturers have started developing eco-friendly models with recyclable materials and energy-efficient designs, further innovation is needed to minimize electronic waste and promote sustainability. Additionally, high costs remain a barrier to widespread adoption, particularly in low-income communities where access to basic dental care is already limited[18]. If not addressed, the affordability gap could exacerbate oral health inequalities, making it essential to explore cost-effective alternatives, subsidies, or government-supported oral health initiatives to improve accessibility. Another critical concern surrounding smart toothbrushes is data privacy and security. These devices collect detailed personal data related to brushing frequency, pressure, technique, and even oral health conditions. While regulations such as GDPR (General Data Protection Regulation) aim to protect consumer data, concerns persist regarding

data ownership, third-party sharing, and potential misuse[22]. To ensure public trust, companies must implement transparent policies, stronger encryption, and user control over data storage and sharing. Without these safeguards, privacy concerns could discourage individuals from adopting AI-driven oral health technologies. Looking ahead, the future of smart toothbrushes extends beyond oral care into broader health monitoring applications. Researchers are exploring the integration of sensors capable of detecting biomarkers for systemic diseases, such as diabetes and cardiovascular conditions, through saliva analysis[23]. This innovation could transform daily brushing routines into a proactive health monitoring tool, allowing users to detect potential health issues early. However, further research is needed to validate these technologies, ensuring their accuracy, usability, and clinical relevance before widespread implementation.

Conclusion

Smart toothbrushes represent a significant advancement in oral healthcare, offering real-time feedback, AI-powered personalization, and enhanced accessibility. Their ability to improve brushing techniques and promote long-term oral health makes them valuable for children, individuals with disabilities, and those with specific oral health concerns. However, barriers related to cost, environmental impact, technological accessibility, and data privacy must be addressed to ensure equitable and sustainable adoption. Moving forward, affordability initiatives, eco-friendly design innovations, and stronger data protection policies will be essential in shaping the next generation of smart oral healthcare solutions. With continued advancements, intelligent toothbrushes could play a transformative role in preventive healthcare, bridging the gap between oral health and overall well-being.

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