Review

Advancing Minimal Intervention Dentistry: Emphasizing Digital Enhancement of Direct Composite Restorations with Refined Bonding Strategies and Innovative Non-destructive Terahertz Internal Observation

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Keywords : Minimal intervention dentistry, Direct composite restoration, Dental Adhesive, Terahertz non-destructive imaging

Abstract : This review sheds light on the evolving trends in Minimal Intervention (MI) dentistry, particularly in direct resin composite restorations. The expansion of resin composite restorations' applications has led to the development of novel adhesive techniques for enhanced bond durability and innovative restoration methods utilizing digital technology. This paper elaborates on smear layer deproteinizing pretreatment (SLDP), which has been found to significantly improve dentin bond durability. Furthermore, we explore the digitally-guided direct resin composite restoration, a method that combines the clinical efficacy of analogue and digital restoration methods. This innovative technique standardizes treatment procedures, reduces reliance on the dentist's skill, and improves treatment outcomes. The review also examines the emerging non-destructive inspection technique, terahertz pulsed imaging, which has revolutionized the internal visualization of the adhesive interface between tooth substrates and biomaterials. The paper underscores the crucial role of digital workflows and the development of new adhesive technique, resin composite materials, and non-destructive testing methods in shaping the future of restorative treatments, collectively termed Advanced MI Dentistry. We call for further basic and clinical studies to continue advancing this vital field.

I. Introduction

The emergence of direct resin composite restorations has significantly reshaped the landscape of dentistry. Acting as a cornerstone of Minimal Intervention (MI) dentistry, these restorations have expanded their applications far beyond traditional dental caries treatment, as defined by G.V. Black. Nowadays, direct resin composite restorations are used in a variety of dental procedures, ranging from the typical restorations to full mouth reconstructions and multiple teeth restorations[1-4]. The introduction of dental microscopes has further enhanced the precision and efficacy of these restorations, leading to their wider recognition and use. Concurrently, advancements in direct bonding techniques have greatly improved the bond durability of direct resin composite restorations, thereby extending their longevity and functionality.

It's important to highlight the crucial role of dentin bonding in the success of direct composite restorations, which relies on the principles of reliable and durable bonding[5]. By utilizing the gold standard 2-SEA system containing one of the most dependable functional monomer, 10-MDP, significant improvements have been achieved in

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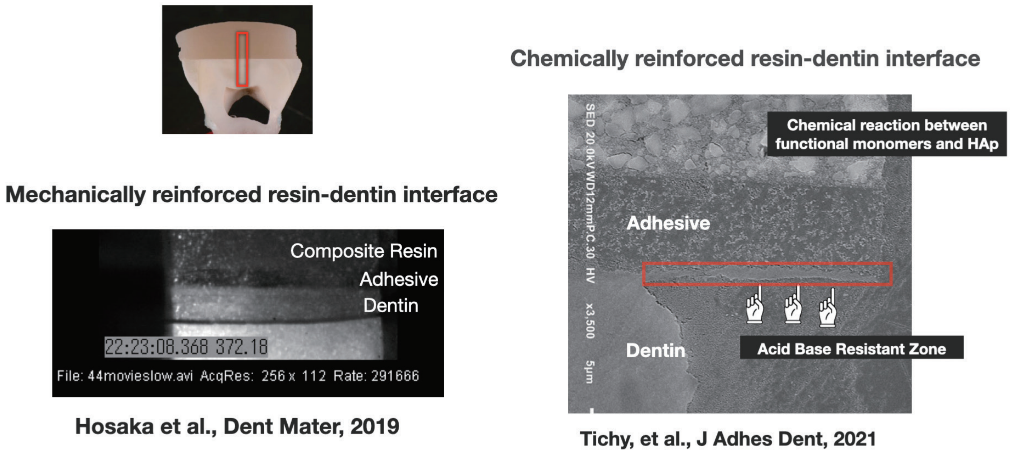

Fig. 1 Mechanically and chemically reinforced "super dentin" [6-8]

the infiltration into dentin, polymerization of the adhesive layer, and copolymerization between the adhesive and resin composite. With the use of ultra-high-speed videography under tensile load for the analysis of fracture dynamics and static morphological observation of resin-dentin bonded specimens aged in acidic and basic solutions, we have been able to reveal interfaces that are mechanically and chemically reinforced beyond the natural human tooth structure[6, 7]. This phenomenon, named "Super Tooth Formation" by Nikaido et al[8], is believed to be a key factor in ensuring the longevity of direct resin composite restorations (Figure 1).

At the same time, the rise of digital technology in dentistry has ushered in new restoration techniques, enabling treatments to be more accurate, efficient, and personalized. Additionally, innovative non-destructive examination strategies have been developed to foster long-term maintenance of direct resin composite restorations, further augmenting their role in preserving dental health.

In this review, we will explore the advancements in adhesive techniques that enhance bond durability, delve into the impact of digital technology on restorative methods, and examine the innovative non-destructive strategies aimed at ensuring the longevity of resin composite restorations.

II. Enhancing bond durability through smear layer deproteinizing pretreatment (SLDP)

The MI dentistry philosophy, initially presented by the World Dental Federation (FDI) in 2000, and subsequently revised, seeks to counter traditional 'drill & fill' procedures that are executed without an exhaustive examination or diagnosis. This paradigm shift focuses on the possibility of managing and controlling dental caries, the imperative of conserving healthy tooth substrates, the principles of minimally invasive functional and esthetic direct resin composite restorations, and the crucial role of pulp protection.

Despite these advancements, untreated dental caries continue to pose a significant global health challenge. The 2013 Global Burden of Disease Study ranked untreated dental caries of permanent teeth and untreated dental caries of deciduous teeth as the first and tenth most prevalent medical diseases, respectively. This data demonstrates that dental caries remains a significant burden for many individuals worldwide[9, 10]. Even in countries with comprehensive public health insurance systems, untreated dental caries remains widespread, emphasizing the need for more precise epidemiological data in oral health research, as noted by Vergnes and Mazevet (2020)[11]. Their study underscores that the fee-for-service model, prevalent in many dental payment systems, often centers on remunerating clinical procedures, resulting in oral diseases often being overlooked in public health policies. Consequently, there's a lack of motivation for epidemiological surveys, even though they're essential for creating an efficient system that optimizes health outcomes. This situation calls for a re-evaluation of oral health policies, possibly incorporating initiatives like fees or bonuses for data collection to encourage dentists to supply critical data for policy improvement.

Minimally invasive caries treatments that aim to minimize dentin removal and maximize pulp preservation promote the concept of selective caries removal. This technique, proposed on Fusayama's two-layer concept of carious dentin[12], stresses the removal of only infected dentin while conserving affected dentin[13]. However, bond strength to caries-affected dentin tends to be weaker than that to sound dentin[14, 15], highlighting the need to select a dental adhesive material and technique that can effectively seal the prepared surface and enhance

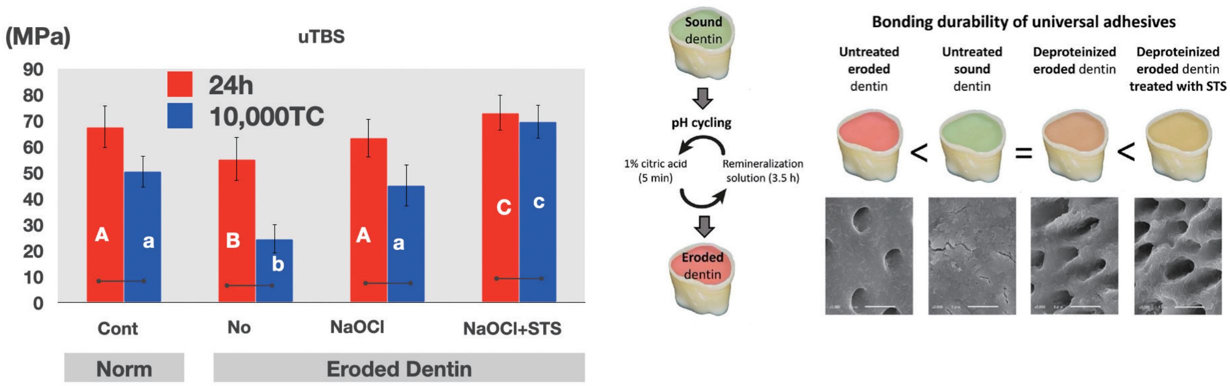

Fig. 2 Enhanced bond durability of universal adhesives on deproteinized eroded dentin.
Abbreviation: STS=Sodium p-Toluene sulfinate

adhesion.

Recent research has spotlighted SLDP as a potential solution. By employing a sodium hypochlorite solution[16-18], hypochlorous acid (HOCl)[19] , or natural enzymes[20, 21], SLDP aims to improve dentin bond strength and durability in self-etch adhesive systems. SLDP works by eliminating the organic phase from the smear layer, thereby facilitating better monomer infiltration and improved polymerization in the remaining mineral phase, which is the target of the functional monomer. Notably, SLDP demonstrates pronounced effectiveness not only on sound dentin but also on caries-affected dentin, where a thick smear layer, rich in organic components, typically forms.

However, the clinical use of sodium hypochlorite solution presents a challenge: oxidants may remain on the treated surface even after rinsing with water, potentially inhibiting adhesive polymerization. To address this issue, an additional application of a reducing agent containing sodium sulfinate salt is crucial. Intriguingly, pre-application of this reducing agent has been found to improve the light-curing performance of the bonding agent[22]. These treatments have also proven effective on eroded dentin[23] (Figure 2).

III. Digitally guided direct composite restoration: A new paradigm

In instances of large dental restoration, the complexity of the procedure often presents significant challenges[24]. These can include technical errors, increased treatment time, and variability in the final outcome. In response to these challenges, Terry et al. pioneered the use of the "Composite injection technique", utilizing a clear silicone index to facilitate the accurate transfer from the simulation model to the final form of the resin composite restoration[25, 26].

This innovative technique involves creating a highly transparent silicone index, into which a highly filled flowable resin composite is injected. The resin composite is then light-cured through the clear index, resulting in a resin composite restoration that closely transfers the functional and esthetic form of the simulation (Figure 3).

The silicone index can be derived either from the dental arch prior to cavity preparation or a prepared wax-up model. Following the addition of an access hole, flowable resin composite is injected and light-cured, thereby achieving a final restoration form closely resembling the simulation. This method effectively reduces the variability typically seen in operator-dependent, freehand placement of resin composite. It also minimizes the need for reshaping and occlusal adjustment using a highspeed diamond bur cutting, thereby enhancing standardization and efficiency within the treatment process.

The emergence of digital technology in dentistry, notably the utilization of intraoral scanners, lab scanners, computer-aided design (CAD) applications, and 3D printers, has allowed for a more refined and standardized process, especially in the production of clear silicone indices. These indices are fabricated on a 3D printed model, which is derived from a digital wax-up model[27-29]. In a fully digital workflow, the index can be digitally designed and directly 3D printed.

At present, however, there are no colorless, transparent, and elastic 3D printable materials suitable for intraoral use available for resin composite injection technique, necessitating the use of colored (dima Soft Splint, blue, Kulzer, Hanau, Germany) materials for clinical applications[29]. Our research has shown that the light transmittance of the blue version is comparable to 50-60% of the transmittance of a clear silicone (Exaclear, GC, Tokyo, Japan) or a clear 3D-printing rigid resin (dima Print Splint clear, Kulzer) (Figure 4). Consequently, this

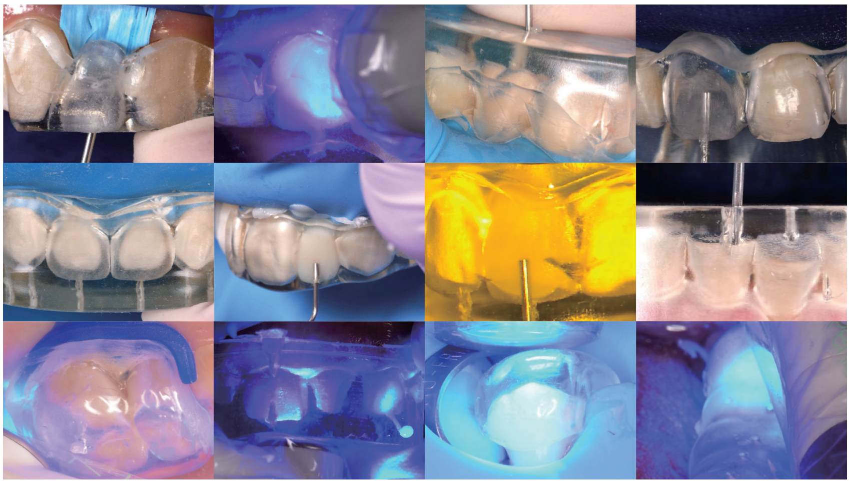

Fig. 3 Direct composite injection technique using a clear index

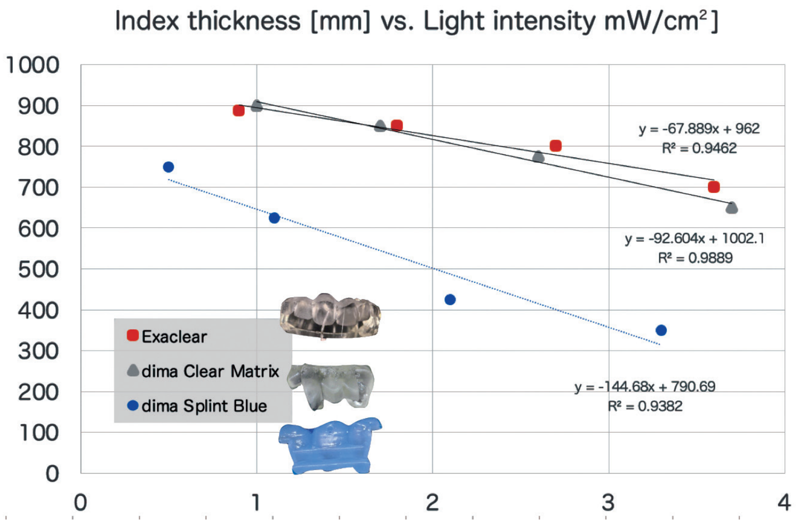

Fig. 4 Translucency of 3D printed resin and clear silicone disks in 1-4 mm thick

flexible 3D-printable resin could be employed as a clear index for the resin composite injection technique. Nevertheless, in the pursuit of more transparent materials, we are actively engaged in the development of new materials suitable for intraoral use.

Despite these significant advancements, the injection technique still requires manual procedures at chairside. To further minimize the technical sensitivity required, we have developed a two-layer index design, featuring a hard clear plastic outer layer (Japanese patent open; 2023-26932), and a stabilization holder design that accurately compresses the clear index, preventing resin composite overflow around the cervical area (Japanese patent application; 2023-075731) (Figure 5)[30]. These enhanced design helps to further streamline the procedure and increase its effectiveness.

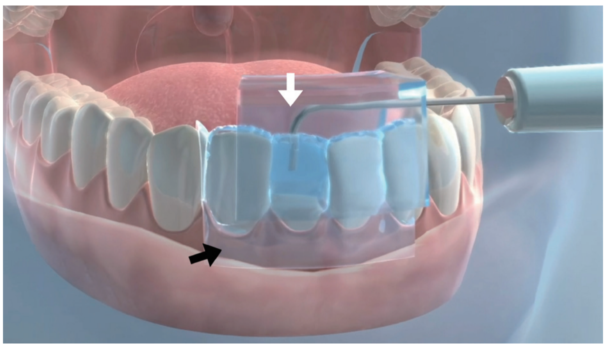

Fig. 5 Fully digitally guided direct composite injection technique using a 3D printed flexible index (Black arrow) with 3D printed rigid stabilization holder (White arrow)[30]

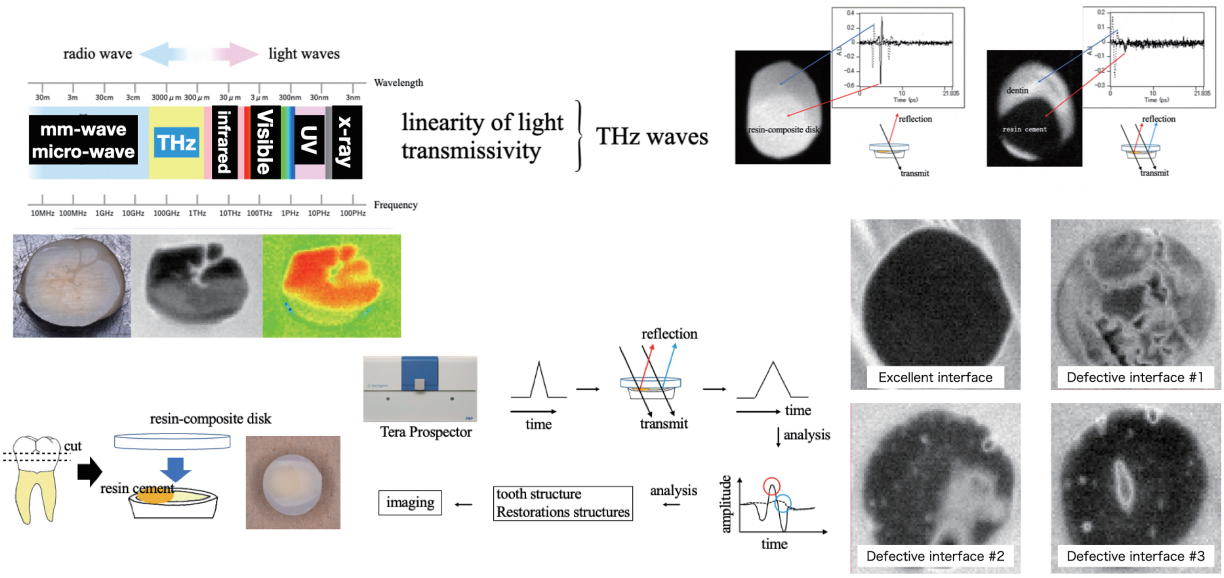

Fig. 6　Nondestructive Terahertz pulse imaging

The digitization of certain aspects or the entirety of the index creation process, through digitally guided resin composite restoration, represents a significant advancement towards standardizing and streamlining chairside and lab procedures. This innovation holds substantial promise for enhancing the efficacy and efficiency of dental treatments.

IV. Non-destructive evaluation and early detection techniques: terahertz time-domain spectroscopy and optical coherence tomography

Non-radiographic dental imaging and inspection technology has recently undergone significant advancements, offering unprecedented opportunities for early caries detection and non-destructive evaluation of restorations. Among these innovations, Optical Coherence Tomography (OCT) is making waves in the dental field. OCT is a non-invasive imaging technology that is effective in detecting early caries and visualizing the internal structure of restorations. This technology leverages near-infrared light to deliver cross-sectional images with micrometer resolution, thereby offering a distinct advantage in detecting dental caries and demineralization at their earliest stages before they are visible to the naked eye or detectable by traditional methods such as X-ray imaging[30]. Another technology, Terahertz (THz) imaging, which bridges the gap between electromagnetic and photonic waves, is gaining recognition for its dental health applications[31, 32].

Our research group has made strides in the non-destructive observation of the adhesively cemented interface between dentin and resin composite disks (Figure 6). By utilizing an innovative terahertz pulsed imaging technique, we have been able to explore the adhesive bonding between human dentin and resin-composite disks. This research involved the use of a luting resin cement to bond these two components, following which a terahertz (THz) time-domain spectrometer was used to assess the reflected THz pulses across time and frequency domains. This pioneering approach enables non-destructive inspection of the adhesively cemented or bonded interface, holding promise for future clinical applications.

This groundbreaking exploration enhances our understanding of dental restoration and opens new doors for the incorporation of terahertz pulsed imaging techniques within the field of dentistry. Our study provides vital insights and accentuates the potential of THz pulsed imaging for non-invasive evaluation and monitoring of dental restorations.

This work highlights the transformative potential of terahertz pulsed imaging in reshaping dental practices, allowing clinicians to assess the integrity of adhesively cemented interfaces without resorting to invasive methods. Besides providing immediate practical benefits, our research lays a solid foundation for further exploration and potential development of terahertz pulsed imaging applications in dentistry, which could lead to improved dental treatment outcomes and elevated standards of patient care.

V. Conclusion

The ongoing development of new adhesive systems, resin composite materials, digital technologies, and non-destructive imaging methods is vital for refining current practices and shaping the future of restorative treatments, termed Advanced

MI Dentistry. While significant progress has been made, the dental community continues to pursue excellence in adhesive durability, accuracy in restoration methods, and the long-term maintenance of resin composite restorations. Continued basic and clinical studies are encouraged to further advance the field.

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Disclosure

In April 2023, the author began a collaborative research project with a corporate partner to develop a clear index with a stabilization clip and offer treatment support, including treatment planning. Additionally, plans are in motion to establish a university startup company to further these innovations.

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