Innovations in Clear Aligner Technology: A Comprehensive Review

[1]Rabia Hussain, [2]Dr.Ravneet Kaur Malhi, [3]Dr. Rajbinder Kaur, [4]Harleen Kaur, [5]Kislay Kumar Anand

[1]BDS Intern, [2]Associate Professor, [3]BDS Lecturer, [4]BDS Intern, [5]BDS Intern

[1]BDS Intern Public Health Dentistry

[1] Desh Bhagat Dental College & Hospital, Mandi Gobindgarh, India

[1]rabiasalani02@gmail.com, [2]malhi.ravneet11@gmail.com, [3]rajbinderk545@gmail.com, [4]kusampreet23@gmail.com, [5]kislaykumaranand4@gmail.com

Abstract- Rapid technological improvements in biomaterials, computer-aided design (CAD) and manufacturing (CAM) have endorsed clear aligner therapy (CAT) as a mainstay of orthodontic treatment, and the materials employed for aligner fabrication play an all-important role in determining the clinical performance of clear aligners. Advances in aligner material chemistry and engineering possess the potential to bring about radical transformations in the therapeutic applications of CAT; in the absence of which, clear aligners would continue to underperform clinically, due to their inherent biomechanical constraints. Herein, this review aims to provide a comprehensive summary of studies regarding direct-3D printing of clear aligners up to the present, outlining all essential properties required in 3D-printed clear aligners and the challenges that need to be addressed. Additionally, the review proposes implementation methods to further enhance the effectiveness of the treatment outcome.

Keywords: 3D printing; orthodontic treatment; aligners; essential properties; challenges; narrative review.

I. INTRODUCTION

The increase in the number of adult orthodontic patients has prompted an upsurge in demand for esthetic and comfortable alternative to conventional fixed appliances, primarily involving braces. Braces are a widely recognized and effective method for straightening misaligned teeth, offering both functional and aesthetic benefits to those who have not experienced the advantage of aligned teeth [1]. The fact that clear aligners are not appropriate for all orthodontic situations presents another difficulty, especially for more serious ones like severe crowding, wide gaps, or biting problems. In certain situations, conventional braces or other types of treatment

can be necessary [2]. Braces which are common in nature used to apply continuous gentle pressure to gradually align teeth and jaws. However, their process carries an inherent risk of prolonged procedure time and associated oral health complications. In order to overcome such kind of issues, CAT emerges as new trend in orthodontic treatment modalities.

Although clear aligners are not a recent invention as Dr. Harold D. Kesling originally promoted a rubber appliance for shifting teeth in 1945, which is when their current usage began. Nahoum created the first thermoformed plastic sheet for moving teeth in 1964 when he created the dental contour appliance. In 1993, Sheridan made modifications to the same and dubbed it the Essix Appliance [1]. These are the active clear plastic trays that fit securely onto the teeth. They are typically worn for two weeks before being replaced one after the other to achieve the integrated tooth movements [3]. There are a number of aspects of CAT that are not fully understood, such as how effective CAT is in comparison to traditional braces and other orthodontic treatments, as well as how long it takes to achieve the desired result and the overall success rate [2]. Hence an attempt has been made through this review article where we have discussed about clear aligner's background, advancement and its sustainability etc in detail.

II. HISTORY

As a discrete and detachable substitute for conventional braces, clear aligners have completely changed the orthodontics industry. However, in the late 1990s, the contemporary clear aligner system became well-known and in the wake of Remensnyder's "Flex-O-Tite" appliance, aligners were introduced. The innovative launch of Invisalign by Zia Chishti and Kelsey Wirth is described, along with the major innovations made by pioneers like Kesling, Nahoum, Pointz, and Sheridan. This was a substantial shift from conventional braces, which accomplished the same thing with metal brackets and wires [4].

Early Concepts and Precursors (Mid 20th century):"Tooth Positioner" the work of 1945 was the first clear aligner prototype which is credited to Dr. Harold D. Kesling. He developed a simple rubber mouthguard-like tool to aid in appropriate tooth alignment. He also recommended using the sequence of these positioners to shift teeth gradually. In 1959–1960s the first known clear thermoplastic dental appliance was made by Henry Nahoum using industrial vacuum-forming technology. These "dental contour appliances" were designed to regulate and alter the shape of teeth [8]. The Material Evolution of the 1980s some appliances made the transition from plastic

to silicon, resulting in "Elastomer Devices" that increased tooth mobility. John Sheridan developed a series of vacuum-formed overlays called the Essix Retainer in 1993 with the goal of reversing tooth motions.

The Birth of Modern Clear Aligners: Invisalign (Late 1990s): Invisalign, the world's first full-length clear aligner system, was created in 1997 and straightens teeth without the need for brackets and wires like traditional braces. The actual breakthrough came in 1997 when Stanford University students Zia Chishti and Kelsey Writh made it. Blending Technology and Orthodontics: Chishti and Writh utilized advancements in 3D computer imaging and CAD/CAM applications. Chishti and Writh created Align Technology, which received FDA certification for the Invisalign system in 1998. This marked the company's commercial launch and FDA approval. After being officially introduced on the market in 1999, it was widely available by 2000. [8]

Evolution and Advancements (21st Century): The usage of intraoral digital scanners is increasing in the digital workflow. Before making aligners, orthodontists can approve or modify the treatment plan using sophisticated software like ClinCheck from Align, which allows them to digitally plan the entire tooth movement process and see the desired outcome. The manufacture of alginers has been revolutionized by the use of 3D printing technology, which allows for incredibly individualized and efficient production. [8] The range of malocclusions that clear aligners may effectively treat has expanded as a result of advancements in research and technology.

Generations of Clear Aligner: Modern alginers' first generation, which emerged in the late 1990s and early 2000s, With Invisalign, the concept of successive aligners is integrated with cutting-edge 3D computer imaging (CAD/CAM) technology. This offers adults an alternative to braces that is more aesthetically pleasing and comfortable. Composite attachments were created in the second generation (mid-2000s to 2010s) to enhance control over complex tooth movements and more precise forces are possible because these little bumps that are glued to teeth give more grip points. From the 2010s to the present, the third generation Automation and Advanced Features Software advancements allowed for the automatic introduction of "pressure areas" and "precision bite ramps" on the lingual of the upper incisors, along with an ideal attachment (ellipsoid bevel), to improve the predictability of deep bite correction. Increased application of AI yields precise and useful outcomes [9].

III. INNOVATIONS AND ADVANCEMENTS IN CAT

Unlike traditional braces, clear aligners are removable, allowing for better oral hygiene and the freedom to enjoy a normal diet without restrictions. As technology advances, so do the capabilities and effectiveness of these alginers.

Shape Memory Material: A subgroup of intelligent materials known as shape memory materials are able to change their macroscopic shape when a suitable stimulus is applied, maintain this temporary shape steadily, and return to their original shape when another stimulus is applied. A subset of shape memory materials are shape memory polymers (SMPs), also referred to as actively moving polymers. Two essential characteristics are necessary for the shape memory mechanism of SMPs to function: a stable polymer network that establishes the material's initial shape and a reversible polymer network that permits the material to change into a temporary or modified shape [3].

Advanced Material Science: The development of clear aligner materials, which are essential to both their effectiveness and the patient experience, has advanced dramatically from early polyethylene terephthalate (PET-G) materials with low elasticity to more sophisticated material with extended elasticity and quick force decay resistance which enable precise tooth movement over longer periods of time. Materials like SmartTrack and advanced thermoplastic polyurethane (TPU) are examples of materials that have reduced thickness and increased mechanical strength through nanocomposites, thanks to advancements in polymer chemistry, nanotechnology, and digital production [10]. A wider commitment to environmental responsibility is also reflected in the industry's growing adoption of sustainable practices, which use plant-based polymers and closed-loop manufacturing processes to reduce waste and encourage recyclability. The advancements in material science and digital technology also contribute to improved clinical outcomes.

Digital Integration and 3D Printing: The aligner workflow has been completely transformed by the use of digital technologies, which have advanced beyond conventional techniques to provide previously unheard-of levels of accuracy and personalization. Fundamental components include 3D imaging, manufacturing CAD/CAM software, and intraoral scanning like Align Technology's iTero [8]. With the aid of these technologies, doctors can create incredibly precise digital models of their patients' teeth, which can then be used to create aligner systems. Digital Light Processing (DLP) and Polyjet are two of the many 3D printing processes

used in this technology. These techniques are meticulously calibrated to alter the chemical structures of printed materials, guaranteeing the aligners' safety and maximum strength.[11].

Aligning and Leveling Anterior teeth: In general, CAT effectively aligns and levels arches in nongrowing subjects. Even Invisalign was very effective in treating anterior crowding but required additional aligners for refinement in 37% of patients [5].

Arch expansion and buccolingual tipping: The latitude for expansion needs to be assessed before treatment, with due consideration for tooth angulation, position in bone and periodontal phenotype. In general, CAT is effective for arch expansion in patients with transverse discrepancies, 96, 97, 98 showing a high degree of efficacy [5].

Bioactive aligner materials: Besides the application of nanoparticles in clear aligner materials for microbial inhibition described previously, when taken intra-orally, these biocompatible products are designed to release many types of ions, including calcium, phosphorus, and fluoride. These ions have the power to prevent demineralization and to start the remineralization and healing process. The findings of the experiment demonstrated that new dental materials with desired bioactive qualities may be created by modifying methacrylate resin, which is used in 3D printing technology, with bioactive glasses. Such accusatory efforts might guide future research on creating novel bioactive 3D-printed aligner materials [4].

Efficacy: In general, some malocclusions can be successfully treated with braces or clear aligners. From an overall mean accuracy of 41% in 2009 to 50% in 2020, the effectiveness and precision of tooth movement (difference between expected and achieved post treatment outcome) with Invisalign have improved. This is primarily due to newer technology, including the more flexible Smart Force aligner material, programmed power ridges, overcorrection’s, and enhanced operator experience [5].

IV. PRESENT RESTRICTION AND CLINICAL ASPECTS

Although CAT is providing the various kind of favorable results while treating the malocclusions but still fewer limitations exist with this innovative newer technology. CAT should not be used when there is significant crowding or spacing problems that requires extractions. Furthermore, some bite problems may be too complicated for CAT to handle well, even with the favorable results in the case of anterior crossbites. Likewise, CAT is probably not going to be strong enough if the patient has complicated skeletal problems or jaw

discrepancies, or if teeth need to be shifted widely in several directions. CAT may be contraindicated if the patient has uncontrolled decay, gingival disease, or active periodontal disease [2]. Finally, the cost of clear aligners may be higher than that of conventional fixed aligners. This is particularly true in more complicated situations where it can take several sets of aligners to get the desired effects. Furthermore, because CAT might not offer the stability and control required for healthy tooth and jaw development, it would not always be appropriate for kids or patients with developmental issues. Traditional braces or other orthodontic treatments might be more suitable in these situations [1]. Nevertheless, CAT is still a relatively new technology, and its application protocols and materials will continue to advance. To address the most serious problems, it might even be feasible to begin with fixed aligners and eventually transition to clear aligners [1].

V. SUSTAINABILITY IN PRODUCTION OF CLEAR ALIGNERS

The clear aligner industry is increasingly recognizing its environmental footprint and is actively pursuing sustainable solutions.

Environmental Issues: Thermoplastic polymers, which are mostly made from fossil fuels, are used to make clear aligners. Throughout their existence, these materials that are useful for orthodontic treatment can contribute to carbon emissions and plastic trash. Additionally, because many aligners are single-use, they end up as garbage after their usage cycle, and the industry's overall environmental impact is further increased by the use of superfluous packaging materials [2].

Innovations in Sustainable Manufacturing Processes and Materials: The industry is going through a major transition to more sustainable manufacturing techniques and materials in response to these issues. Bio-based plastics, which are made from renewable materials like sugarcane or corn starch and are intended to be recyclable or biodegradable, are being investigated and used. The use of recycled thermoplastics in the manufacturing of aligners is also becoming more popular. One example of this is GT FLEX GREEN, which is promoted as the first plant-based, 100% compostable material for clear aligners and retainers in the world. Notably, plastic waste has decreased by 50% thanks to 4D printing technology. The proactive creation of waste-reducing manufacturing techniques and compostable materials demonstrates an industry-wide understanding that environmental stewardship is essential for long-term sustainability and customer appeal [7].

Models of the Circular Economy and Recycling Programs: Some businesses are implementing recycling programs that let patients return worn aligners for appropriate disposal or repurposing in order to address post-treatment waste. To close the material loop, the industry's long-term strategy calls for the creation of circular economy models and entirely biodegradable aligners that break down organically without endangering the environment [7].

VI. PRIORITIES FOR RESEARCH AND FUTURE DIRECTION

The behavior of plastic materials and the responses of tooth movement have been better understood thanks to recent orthodontic aligner therapy studies. To offer evidence-based clinical data on the following, however, a great deal of study is required:

Factor influencing the choice between aligner modification procedures that last seven, ten and fourteen days. The degree of in vivo performance of optimized versus conventional attachments for all tooth movement types except rotation and extrusion. The software accuracy in determining how much interproximal enamel reduction is required to allow for the required tooth movement that would be clinically achieved. The degree to which the various tooth movements are overcorrected in order to compensate for the inherent incapacity of the plastic material to either effectively express the desired tooth movement. An enhancement in the predictability of software simulations of clinical treatment outcomes those are actually feasible. The precision of the gingival margin height forecast changes with tooth movement, including extrusion and incursion [6].

VII. DISCUSSION

Since its origin, clear aligner therapy (CAT) has seen tremendous evolution, progressing from basic rubber appliances to an advanced orthodontic treatment powered by technology. It has been claimed through reported literature that the quick advancements in biomaterials, computer-aided design (CAD) and computer-aided manufacturing (CAM) are directly responsible for this transformation. The experts quoted concur that transparent aligners still have drawbacks that keep them from being a panacea, notwithstanding these developments. However they admit that there are still several unanswered questions regarding CAT, including its long-term success rate, precise treatment duration, and overall efficacy in comparison to standard braces.

Clear aligners will continue to operate poorly because of its intrinsic biomechanical limitations unless material chemistry and engineering advancements are made. The move from early polyethylene terephthalate (PET-G) to

more sophisticated polymers like SmartTrack and thermoplastic polyurethane (TPU) as discussed by Yashodhan M. Bichu et al. (2023) in their study[3]. This advancement is further demonstrated by the creation of shape memory polymers (SMPs), which enable aligners to change and maintain a transient shape before reverting to their initial configuration.

From a sustainability standpoint, the clear aligner industry is becoming more conscious of its environmental impact, according to Monica Macri et al. (2024) [7]. The materials, which are mostly thermoplastic polymers derived from fossil fuels, add to plastic waste and carbon emissions. In response, the industry is moving toward sustainable methods, such as using recycled materials and bio-based polymers. The creation of the plant-based, biodegradable polymer GT FLEX GREEN is cited as an excellent illustration. Additionally, the authors point out that 4D printing technology has resulted in a 50% decrease in plastic waste. Lastly, in order to build a better body of data, the authors and experts such as Daniel Sim and Mauro Farella point out important areas for further study [6]. In order to better reflect clinically feasible outcomes and increase the accuracy of gingival margin height estimates during tooth movement, the authors stress the necessity of improving the predictability of software simulations.

VIII. CONCLUSION

Clear aligner technology (CAT) offers a comfortable and appealing substitute for traditional braces and completely transformed the orthodontics. Innovations in digital technology, manufacturing, and material science have all contributed to CAT's success. The spectrum of situations that clear aligners may successfully treat has increased thanks to innovations like shape memory polymers, sophisticated thermoplastic materials, and 3D printing. But more of research is still required in order to improve CAT's predictability and effectiveness. The technology is anticipated to become even more accurate as it develops further, and for best results, it may be used with conventional appliances.

REFERENCES

1. Kundal S, Shokeen T : Aligners: The Science of Clear Orthodontics 2020;7(1):38-39
2. Almogbel AA : Clear Aligner Therapy: Up to date review article 2023;12:37
3. Bichu Y M., Alwafi A, Liu X, Andrews J, Zou B, Ludwig B, Bichu A Y.: Advances in orthodontic clear aligner materials 2022;22:395-398

4. Ahlawat S, Prabhakar M, Nindra J: Evolution of clear aligner 2022;2:515-518

Amin A.: Advancements in clear aligner technology: What's new in 2024 [Internet]. QuiteClear; 2024 June 10 [cited 2025 Sep 16]. Available from: https://quiteclear.io/advancements-in-clear-aligner-technology-whats-new-in-2024/

5. Sim D., Farella M.: Methodological issues in current clear aligner research, Seminars in orthodontics 2025;8:6

6. Macri M., D'Albis V., Marciani R., Nardella M., Festa F.: Towards Sustainable Orthodontics: Environmental implications and strategies foe clear aligner therapy 2024;17:2-3

7. Nakhate TS, Kangane S, Joshi YS, Bhutada PB, Nair S, Bhoir A.: Evolution of orthodontic aligners: A narrative review. J Oral Res Rev 2024;16(2):171

8. Jangala R, Kamasani S, Gupta KVPT, Khan MU, Rajan M, Shah SS: Orthodontic clear aligners - A review. J Adv Med Dent Scie Res 2025;13(1):17

9. Cenzato N, Di Iasio G, Martin Carreras-Presas C, Caprioglio A, Del Fabbro M: Materials for clear aligners - A comprehensive exploration of characteristics and innovations: A scoping review 2024;14:2-4

10. Narongdej P, Hassanpour M, Alterman N, Rawlins- Buchanan F, Barjasteh E: Advancements in clear aligner fabrication: A comprehensive review of direct-3D printing technologies 2024;16:4