Direct 3D printing aligners – past, present and future possibilities

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Key points

The current trend is the replacement of analogue dentistry with digital and 3D printing technologies, which offer many advantages, such as reduced costs, greater treatment customisation and improved treatment outcomes.

3D printing aligners allows for control over material thickness, potentially providing increased precision in tooth movement, both in anchorage control and staging of tooth movements. This may overcome some of the limitations with using current thermoformed aligners.

Graphy is currently the leading company in the world that manufactures resin specifically for 3D printing clear aligners.

Abstract

The aim of this paper is to introduce the general dentist to recent advances in 3D printing technology used in orthodontics. 3D printing is a highly evolving area of dentistry with continual developments. New advances now allow the in-house delivery of printed aligners. Advocates of this new technology suggest the benefits of more prescriptive and controlled tooth movement in comparison to conventional thermoformed appliances. However, there is currently limited evidence on the efficiency of this material and more research needs to be carried out to validate this new technology.

Introduction

Considered now the fourth industrial revolution, additive manufacturing, or '3D printing' (three-dimensional printing), is a rapidly evolving field, with multiple applications in modern dentistry. One common application is the use of 3D printing to produce orthodontic aligners. Orthodontic aligners are removable, transparent trays used in orthodontic treatment that apply controlled forces to reposition teeth gradually and accurately, offering an aesthetic alternative to traditional braces. Currently, the majority are made from thermoforming a sheet of laminate medical-grade plastic over a dental model. The models used in the thermoforming process are typically 3D printed.

The shift from analogue systems, such as conventional impression taking, to a more digital workflow has allowed for the rapid capture of 3D dental information. Digital manipulation of this information provides the ability to produce aligner appliances in-house. Further developments with computer-aided design (CAD) and modern, user-friendly software now allows practices to sequence their own aligner stages, instead of outsourcing to companies, such as Align or Spark.

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CAD and computer-aided manufacturing (CAD/CAM) is available to any practice at varying price points. Practices can choose entire printer ecosystems or purchase individual printers and software. With advancements in 3D printing and also material selection, it has now become possible to 3D print aligners directly, instead of the conventional method of 3D printing a model for aligners to be thermoformed around. This article introduces the reader to the development of 3D printing CAD/CAM within orthodontic aligners and the advantages and disadvantages of different approaches and technology. The article will also discuss the potential impact 3D printing of aligners could have on the dental industry, as well as some alternative aligner technologies.

History of 3D printing and clear aligner therapy

In 1971, Johannes F. Gottwald obtained a patent for an invention known as the liquid metal recorder, which aimed to organise liquid metal droplets into a predetermined configuration that would solidify into a metallic object upon drying. Gottwald pioneered the concept of rapid prototyping which served as a precursor to modern-day 3D printing techniques.[1]

Just over a decade later, in 1986, an American inventor, Charles Hull, coined a method of additive manufacturing after using ultraviolet (UV) light to harden multiple resin coatings on tabletops. He named this technique 'stereolithography' (SLA) and it would become the first commercial 'rapid prototyping' technology. The SLA process involves using photo-sensitive polymers to build an object using successive layers and an UV laser to consecutively polymerise, combine and solidify each layer.[2]

Prior to the 1990s, the fabrication of orthodontic aligners was a slow process and involved manual drafting and wax setups.[3] A thermoplastic appliance was created using the wax setup that could be used as both a retainer and a tooth positioner.[4] Orthodontic movements were possible by creating divots or adding projections on the tooth surface.[5]

In 1997, Zia Chishti, from his Stanford dorm room, made use of CAD and SLA to print dental models, in which thermoformed aligners could be produced. The US Food and Drug Administration granted approval for this device in 2000, and their company, Align Technology (Align Technology, Inc. Arizona, USA), became the first clear aligner company, destined to become the largest global 3D manufacturer of aligners.[6]

Initially, aligner companies required a physical impression which would be converted to digital files using industrial scanners. This efficiency of the manufacturing and delivery process was amplified with the launch of intra-oral scanners. This advancement also facilitated the incorporation of CAD technology, eliminating manual drafting and multiple-sectioned models. Scans could be imported into modelling software where algorithms, design models with incremental tooth positions. These sequential models were then sent to 3D printers to produce aligners.

Clear aligner technology has rapidly evolved in the past decade, with the mass adoption of digital technology and significant investment from multiple stakeholders in the dental marketplace. Recent advancements have provided the ability to 3D print aligners directly without the need for thermoforming using a printed model.

3D printing

As mentioned previously, 3D printing is the process of making a physical object from a 3D digital model, typically by laying down many thin layers of a material in succession. The process starts with a digital file, known as a STL file, though other file types are also used.[7]

Prior to printing, STL files can be modified using software that creates a 3D virtual environment. Many different CAD software solutions are currently available, but popular orthodontic programs include Maestro 3D Ortho Studio, Planmeca Romexis Ortho Studio, RayWare and FreeForm.

These programs allow an orthodontist to plan individual tooth movements or design appliances. Once tailored, the STL files can be sent to the printing software.[8,9]

Within dentistry, the main two types of printers utilised are SLA and digital light processing (DLP) printers (Fig. 1). They both operate in similar ways by selectively curing photosensitive resin in layers to create a solid object. The main difference is that DLP printers use a digital projector whereas the SLA printers use a UV laser. DLP printers are faster than SLA printers as they can cure an entire cross-section of resin in one go, whereas SLA printers cure in a co-ordinated sequence which takes longer. However, the digital projector in DLP printers can succumb to surface finish errors.[10]

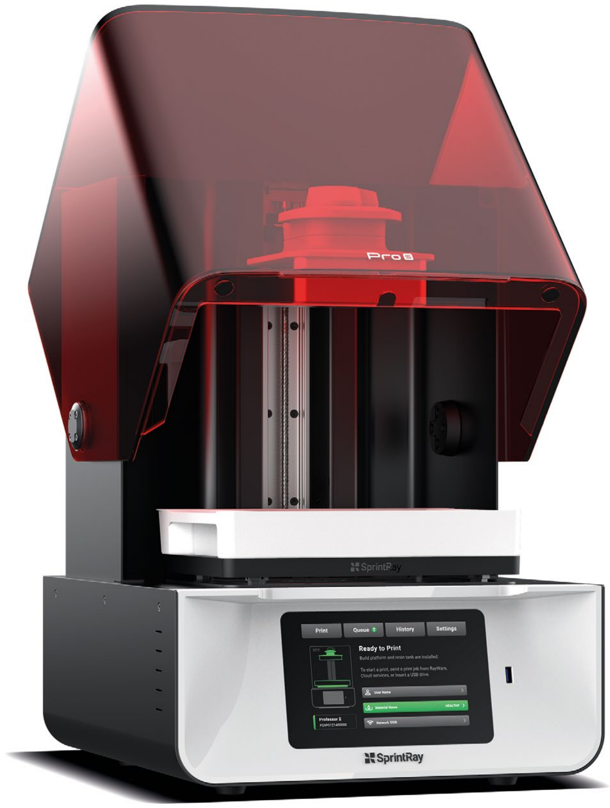

Fig. 1 Digital light processing printer by SprintRay (Los Angeles, California USA). Image reproduced with permission from SprintRay (sprintray.com)

Table 1 Comparison of SLA and DLP 3D printing technology[10]

Features	SLA	DLP
Source	Laser	Projector
Resolution	Higher resolution and can deliver consistent 25-micron resolution	Resolution between 25–100 microns
Accuracy and precision	Delivers good accuracy/precision, but very dependent on printer calibration and materials used	The differences in accuracy is explained by variations in the machinery rather than differences between the technologies themselves
Build volume	Build volume independent from resolution so technology is scalable	Trade-off between build volume and resolution. The larger the volume, the lower the resolution (due to the projector and voxel formation)
Surface finish	Superior surface finish of DLP but usually only visible on complex 3D prints	Voxel formation leads to lower surface finish on complex models
Speed	Slower than DLP	Faster than SLA
Materials	Multiple material types for various dental modalities	Multiple material types for various dental modalities

Each printer type can deliver the precision needed for dental applications, but the quality can vary drastically between various printers and the numerous settings that can be selected. Companies such as SprintRay and FormLabs are leaders within the industry and have various printers available to suit individual practice needs.

See Table 1 for a summary of the main differences between the two different printing technologies.

Conventional workflow for the production of clear aligners

Conventionally, an aligner is made from thermoforming medical-grade laminate plastic around a model. This process begins

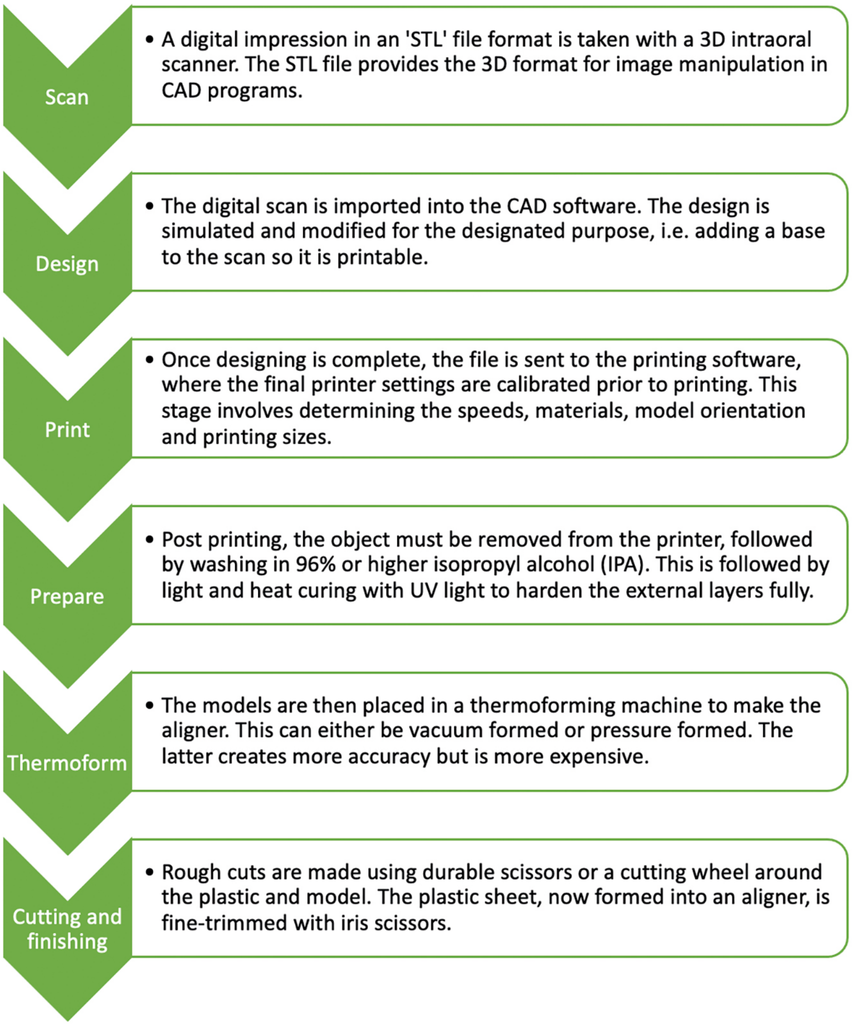

Fig. 2 3D-printed model workflow for thermoformed retainers/aligners

Fig. 3 Graphy direct aligner printing. Image reproduced with permission from Graphy Inc (http://itgraphy.com)

when a digital scan is taken of the mouth using a digital scanner, producing an STL file. This STL file is then manipulated within the software by a lab technician, if outsourcing for clear aligner production, or by the clinician. Once the file has been manipulated into a 3D-printable model, it is sent to the printer. At the printer, the settings are altered to meet the requirements for the model, such as thickness, printing speed and sizes. Manufacturers have specific resins and materials for various treatment needs and therefore model-specific resins are chosen.

Once printed, the model enters a stage of post-processing. Here, the model is removed from the printer and washed in a solution of isopropyl alcohol, which removes the top layer of uncured resin. Once completed, the model must be cured under UV light, usually within a curing unit.

The final step is the production of the aligner. The model is placed within a thermoforming unit where the medical-grade plastic is either pressure-formed or vacuum-formed around the model. This workflow is completed by trimming the excess plastic. The models and plastic scrap are discarded and then the aligner/retainer is ready for use. This process has been summarised in Figure 2.[11]

Direct aligner printing

The traditional method of producing an aligner has a huge environmental toll.[12] There is significant wastage as the corresponding model serves no further purpose after the thermoforming process. Direct aligner printing aims to overcome this issue, negating the need for a model in the production process.

Until recently, insufficient material properties prevented the ability to directly print aligners. In 2019, a South Korean company, Graphy (Seoul, South Korea), developed and released a novel aligner resin: Tera HarzTM TC-85DAP (Fig. 3). The material exhibits flexibility and heat-resistant properties required for an aligner. In addition, if the material is deformed or stretched, it can be restored when it comes into contact with hot water. Most importantly, the material can be used with compatible 3D printers to directly print the aligners in-house. The workflow to produce a direct aligner is outlined in Figure 4.

Advantages of directly printing aligners

See Box 1 for advantages of directly printing aligners.

Cost saving

Without the need for printed models, the material costs of the process are reduced.[13]

Ecological effects

Due to the resin-curing process in the manufacture of plastic models, they cannot be recycled. They are destined to end up in landfill, increasing the risk to the environment, as well as health concerns of microplastics.[14] Directly printing aligners negates the issue of model wastage. However, aligner disposal is still a problem.

Biocompatibility

Initial studies show that the 3D-printed aligner resin is safe for use and has been shown to have no cytotoxicity or oestrogenicity effects.[15]

Accuracy

Early *in vitro* studies have indicated increased accuracy over thermoformed aligners.[16] Future evidence is required to determine if this has an effect on treatment outcomes and treatment predictability.

Material properties

One issue with conventional thermoform aligners is the loss of force through 'stress-relaxation'. Graphy claims to have overcome this issue with a shape-memory property of their printed aligners.[17] The shape-memory property is achieved by placing the aligners in hot water, where they return to the original printed shape. This mimics the process of reactivation and potentially delivers an enhanced force delivery to the teeth.

Customised design

The thickness of the aligner can be customised within the modelling software before printing. This allows for customised treatment and more control over individual tooth movement. Variable aligner thickness allows the manipulation of different areas of the aligner, whether for anchorage, greater activation, or even creating a counter-moment for root movement.[18] The reported benefits suggest this allows for bodily movement of teeth, in comparison to current clear aligner systems, which can only tip teeth.

Faster

Directly printing aligners require fewer steps and less delay in manufacture. The removal of a supply chain can improve efficiency versus a traditional workflow.[13]

Disadvantages of directly printing aligners

See Box 2 for disadvantages of directly printing aligners.

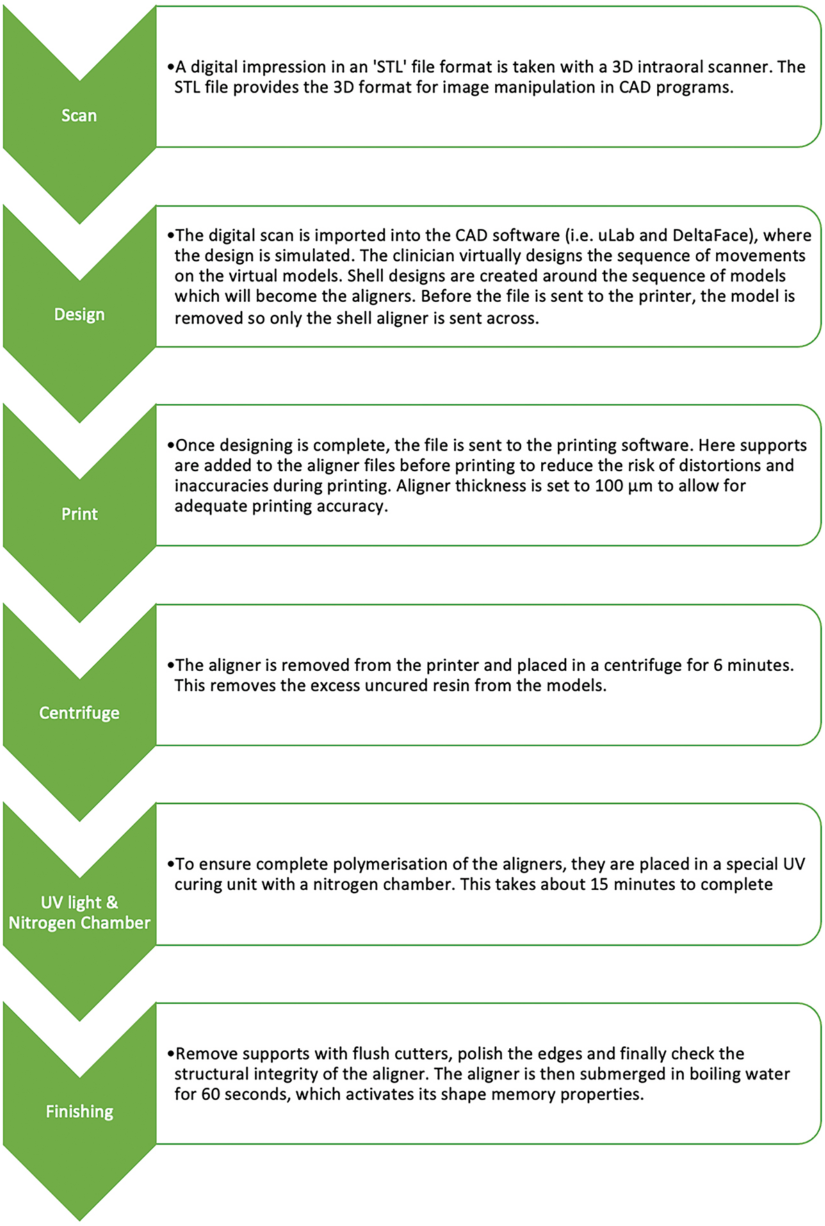

Fig. 4 Workflow for directly printing aligners

Software compatibility and time consumption

CAD software is currently limited to a small number of companies, for example, uLab, DeltaFace or Maestro. 3D compatibility with different CAD programmes and printers may not be feasible. In addition to this, certain modifications must be manually added to the aligners, reducing the efficiency of the process.[13]

Increased cost

Specialised resin is required, which has a higher cost compared to conventional resins. In addition to this, a specialised UV and nitrogen curing unit is required for the aligner resin produced by Graphy, which will increase the gross cost of the production. When considering the purchase of this technology, a return-on-investment calculation needs to be determined to assess if printing aligners is financially viable or whether it is better for the practice or clinician to outsource to existing aligner systems.[19]

Lack of evidence

The significant disadvantage is that the current evidence on this material is extremely limited and of low quality. Many of the early studies on the effectiveness of this material are *in vitro* studies and suffer biases due to limited sample sizes and limited data available. More high-quality, prospective, randomised studies are required to validate this technology and affirm the aforementioned reported advantages.[13,20]

Box 1 Advantages of directly printing aligners

- Cost savings
- Positive ecological effects
- Biocompatability
- Accuracy
- Material properties
- Customised design
- Faster

Box 2 Disadvantages of directly printing aligners

- Software compatibility
- Time consumption
- Increased cost
- Lack of evidence

Is this the technology of the future?

The possibility of providing more prescriptive, controlled and efficient tooth movements is always sought after. While direct 3D printing is one avenue for advancing technology, the available evidence is limited. Therefore, other technologies that utilise existing materials have also been developed.

The Clear X aligner system is an example of a shape-memory polymer reported to reduce the number of aligners needed, thereby reducing the plastic waste associated with each aligner case. Materials like this, if widely adopted, may serve as a bridge for environmental issues surrounding aligners until enough research has been obtained to validate the use of direct 3D-printed aligners.

Conclusion

3D printing has evolved in the last ten years, but the technology is still in its infancy. Compounding this, direct aligner printing is at an even earlier stage of development. The technology is promising and may overcome many of the issues currently faced in aligner systems and tackle the environmental effects of the disposal of models.

The processes must be refined and more product development must be done to improve the material qualities. Research on force delivery, dimensional stability and degradation of aligners should be focused on. Robust and reproducible results must be demonstrated at a larger scale to ascertain that directly printed aligners are superior in mechanical properties, or at least comparable. Independent primary research should be carried out to validate this. Once this has been achieved, it can be determined whether this is the future for orthodontic technology.

Ethics declaration

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

Jack Slaymaker was responsible for the conceptualisation of the paper topic. Jack Slaymaker, Sunil Hirani and Julian Woolley were all involved in writing the original draft, editing and reviewing the manuscript.

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