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Review Article

3D Printing in Orthodontics: An Introduction

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Abstract

Aim: To introduce 3D printing to individuals or practices providing orthodontic treatment.

Introduction: 3D printing or additive manufacturing is the fabrication of objects from a 3D digital model. 3D printing can be achieved by the successive deposition of photo-sensitive resin material, cured solid with a light source such as a laser. This allows for customisable appliances and improved workflow in practice. 3D printing is a rapidly evolving technology, with many practices beginning to implement it into their digital workflows. Adoption and integration come with many challenges.

Conclusion: Provided suitable materials and 3D printing protocols are followed, 3D-printing produces accurate and robust dental models without the errors associated with conventional dental impressions and plaster models. While this involves the transition from conventional methods of fabrication and outsourcing to a fully digital workflow, savings and improved efficiencies can result.

***Keywords:** 3D-printing, Additive Manufacturing, Aligners, CAD, SLA, DLP, Digital Orthodontics, Digital Workflow*

Key points

1. There are many different types of 3D printing, but the main types utilised within dentistry and orthodontics use light curable resin. A light curing source cures sequential layers of resin until the desired 3D object has been formed.
2. 3D printing is becoming more commonplace in practice, due to affordability of the technology and can improve efficiencies and accuracy when compared to an analogue process.
3. 3D printing has many applications including, but not limited to; aligner printing, bracket printing, splints, retainers and transfer trays.

Introduction

Three-dimensional (3D) printing is defined as the process of making a physical object from a three-dimensional digital model. The concept was introduced by Johannes Gottwald in 1971. Gottwald created a device that used liquified metal, which would then solidify into a shape upon each successive layer [(1)]. In 1984, Charles Hull developed this further and built on this technology by using photo-sensitive polymers to build objects using successive layers and lasers to solidify each layer [(2)]. This became known as *stereolithography*.

Stereolithography in the field of dentistry faced early challenges related to scalability, hindering its widespread adoption. However, a significant turning point emerged in the early 2000s with the advent of intra-oral scanners, which revolutionized the conversion of analogue dental processes into digital ones.

This breakthrough rekindled the momentum for 3D printing advancements. Subsequently, technology has progressed at an accelerated pace, propelling orthodontics from an analogue era into a digital landscape. The primary objective of this paper is to provide an insightful overview of 3D printing's integration within orthodontics, with a focus on the contemporary digital workflows empowering clinicians to seamlessly incorporate this transformative technology into their daily clinical practices. The paper will summarise the key components of the workflow, and then discuss the benefits, disadvantages and future of 3D printing in orthodontics.

The 3D printer workflow

The printer workflow is outlined in Figure 1, but can be summarised in 4 key steps:

1. **Scan** – A digital scan is recorded and sent to the lab as an 'STL' file. This file provides the 3D format for image manipulation in CAD programs.
2. **Design** – The digital scan is imported into computer aided design (CAD) software, where the design is simulated.
3. **Print** – The file is then sent to the printing 'slicing' software, where the object is made ready for printing. The slicing software involves setting up model supports, printing speed, determining material options, and printing size.
4. **Prepare** – Post printing, the object must be washed, dried, and post-cured. Prints are washed in 99% isopropyl alcohol (IPA) and cured using heat and ultraviolet light.

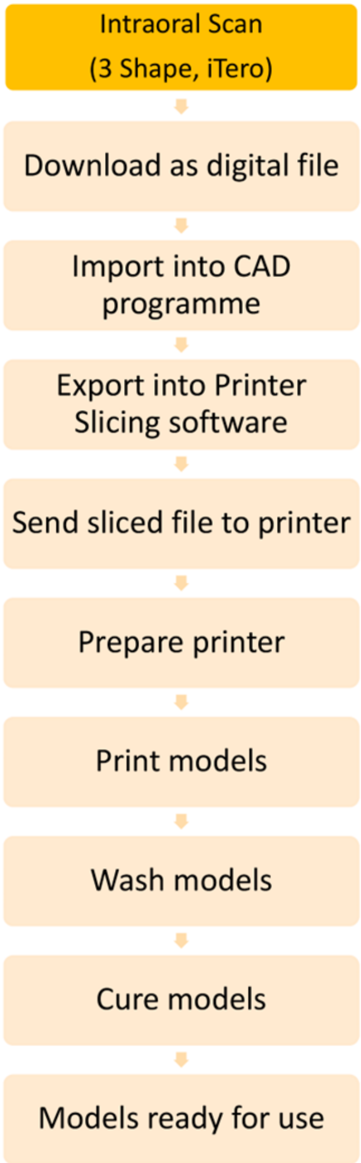


Figure 1: *Workflow for use of digital printer (3, 4)*

Software requirements for 3D printing

Software is required and takes the form of Computer-Aided Design (CAD) programs. CAD programs create digital models in 2D or 3D. This enables the visualisation of a model prior to construction, replacing the manual drafting of objects. CAD allows for rapid development and modification of designs through renderings before resources are used for production. Once designs are finalised, they are sent via a file called an 'STL' file to a slicing software to prepare the digital model for printing (Figure 2).

Dentistry-specific 3D printers have an ecosystem of hardware and software. Typically, CAD programs require extensive training and orthodontists do not necessarily have time for that. Therefore, many of these programs have automated processes and features that auto-populate functions to improve the design and processing through printing. These programs contain slicers built into the CAD software so the design can be sent straight for printing.

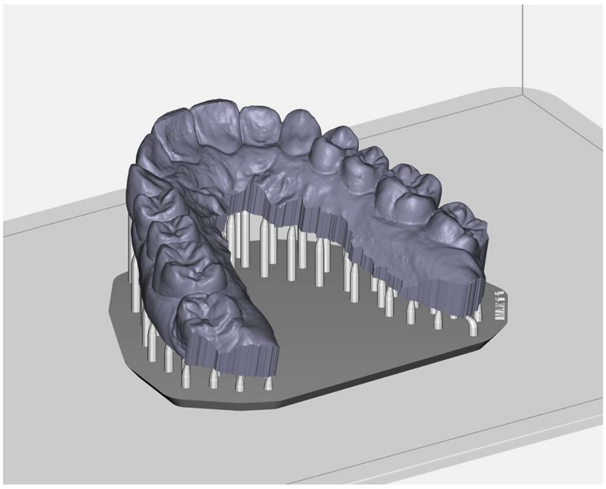


Figure 2: *Rayware Program from SprintRay illustrating model printing. The model is stabalised using ;supports'*

3D printer types and quality

The predominant 3D printing technologies employed in orthodontics encompass Stereolithography (SLA) and Digital Light Processing (DLP), as depicted in Figure 3. Historically, these methodologies were characterized by their high costs and complexity. However, contemporary advancements have streamlined them to the extent that they can now be conveniently accommodated on a desktop, facilitating the production of high-quality prints while significantly mitigating expenses.

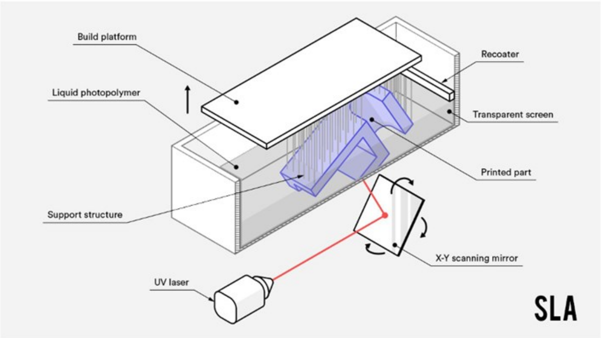
Figure 3: *SprintRay 3D printer. Source: SprintRay.*

Although both SLA and DLP technologies possess the capacity to achieve the precision and accuracy crucial for orthodontic applications, it is imperative to acknowledge that the quality of outputs may exhibit substantial variations among different printer models.

When comparing printers, accuracy is one measurement to determine the printer's quality. Accuracy is how close a measurement is to the true value. The true value represents how closely the 3D-printed design is to the computer-simulated [5]. Other measures of printer quality include precision and consistency [6].

Stereolithography (SLA)

To begin printing, a build platform is lowered into a resin tank with a distance of one layer height between the build platform and the photosensitive liquid resin or the last completed layer. A UV laser is directed to specific coordinates to cure the resin. Two mirrors help direct the laser to the specified coordinates and light cure sequence. This newly formed solidified layer separates from the bottom of the resin tank, and the platform moves up, allowing for fresh resin to flow into the space. This subsequent layer is then cured and the process repeats until the print is finished (Figure 4). Layer height can be altered, but the smaller the layer height the more accurate the print. After completion, the model can be peeled off the build platform and is then subjected to post-processing, which will be covered later in the paper.



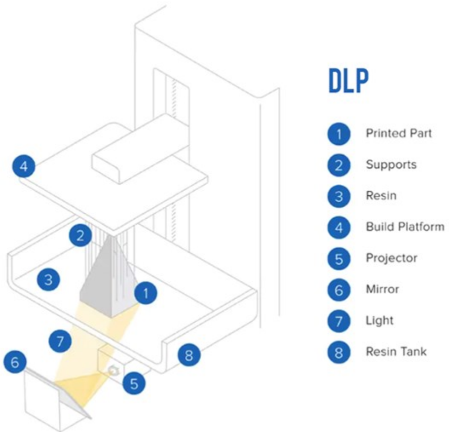


Figure 4: *SLA and DLP printer schematic. Source: Protolabs HUBS and FormLabs, respectively.*

Digital Light Processing (DLP)

DLP printers are built around a resin tank. The platform is lowered into the resin tank, and one layer height is left between the platform and the resin. A projector screen is used to flash and cure the resin via mirrors. Curing happens across all points simultaneously (Figure 4). The platform moves up to allow for the fresh resin to fill the layer height and then cured once more. The cycle is repeated until the object is complete. This is faster than SLA printing as the DLP projector instantly cures the entire cross-section of resin rather than following a sequence of coordinates.

Comparison of SLA and DLP printers

One of the significant differences between the two printer types is the resolution. In SLA printing, the laser's cross-section is circular, so the lines are rounded and smooth as the laser is curing resin. In contrast, the DLP uses a digital projector, so the print resolution is only as good as the projector. The digital projector creates pixels, known as voxels, creating a less accurate surface finish when curing.

This becomes more apparent on curved edges as the smallest pixel size is square, thus creating a step in the final print (Figure 5). In addition, SLA printers start from £3000, and DLP from £7000 [7]. Further differences are summarised in Figure 6.

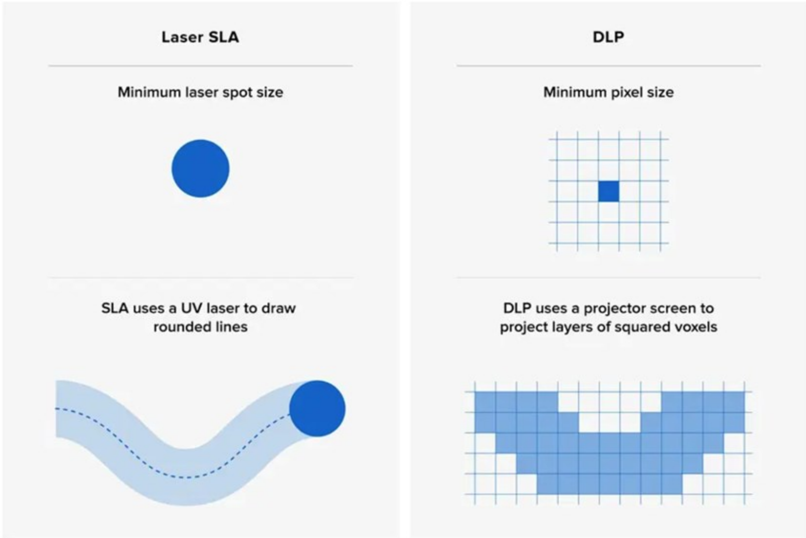


Figure 5: *Voxel Formation in DLP Printers.*

SLA Advantages

- Accurate
- Smooth surface
- Complex printing patterns
- Easy ergonomics
- Variety in material choice
- Small footprint

SLA Disadvantages

- Not enviromentally friendly due to resin usage and wastage
- Objects require post curing
- SLA is slower than DLP

DLP Advantages

- Accurate
- Complex printing patterns
- Faster than SLA printing
- Variety of material options
- Small footprint

DLP Disadvantages

- The surface finish is not quite as good as SLA
- Smaller build volume – due to digital projection (the larger the volume, the more voxel formation, so the build quality is reduced)
- Objects need post curing
- More expensive than SLA

Figure 6: *SLA and DLP Advantages and Disadvantages (8).*

Processing of 3D printed products

After printing, there are three steps required before the appliance/model is ready for use. These include:

1. Washing

The main method of washing involves using a washing station machine featuring a 99% isopropyl alcohol (IPA) tank to clean the appliance. Another method involves using a ultrasonic bath. This uses a tripropylene glycol monomethyl ether (TPM) solution instead of IPA, as the latter is flammable and unsafe for use with an ultrasonic bath [9].

2. Removing Supports

Some intricate appliances require supports to stabilise the appliance during printing (Fig. 5), which can be broken off by hand or removed with a flush cutter. After which sandpaper can be used to improve the final surface texture.

3. Curing

Curing the appliance under ultraviolet (UV) light is crucial to allow for the final material properties to be achieved. The curing time varies depending on the manufacturer and the material used. A specific curing station is used and is often available from the printer manufacturer.

Advantages And Disadvantages of Digital Versus Conventional Methods

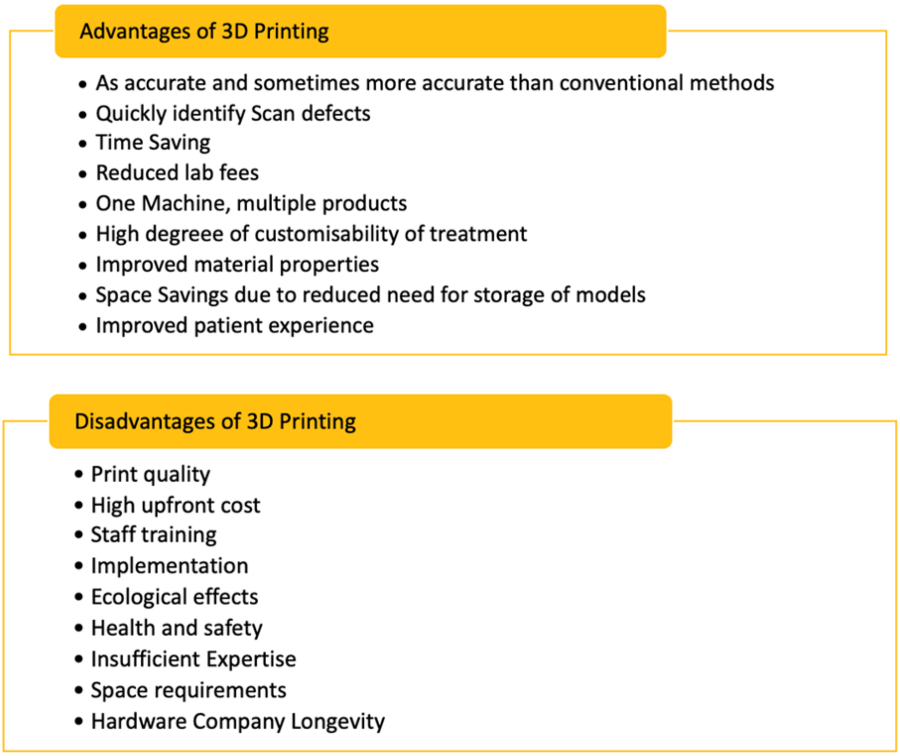


Figure 7: *Advantages and Disadvantages of 3D-printing* [4, 8, 10, 11]

Advantages of Digital over Conventional Methods

Accuracy

Scanning and 3D printing are as accurate as conventional impressions and models in the context of orthodontics. A common product of 3D printing is an orthodontic model [6, 10, 12, 13]. Conventional model production is prone to technical errors at the different stages of production. Some examples include distortions created by the impression technique, extended alginate disinfection or improper storage. These can affect the outcome and accuracy of the model. With 3D printing, many of these issues are overcome due to reduced steps, which can improve the model's accuracy.

Another use of 3D printing is the process of creating transfer trays to seat brackets in the indirect bonding technique. Accurate bracket positioning is a vital step in treatments and can influence the results and duration of orthodontic treatments. The conventional process requires many stages, which can increase inaccuracies, from impression distortions of the model to discrepancies in the pick-up materials [14].

Scan defects

In conventional impression taking, clinicians check for defects in the impression prior to sending to the lab. Defects or undercuts can be troublesome to locate. Scanning allows for defects to be easily and rapidly identified, and adjustments can be made by rescanning or image manipulation, reducing the need to recall the patient or return lab work. Although not directly related to 3D printing, this advantage is gained through the workflow and, therefore, can be seen as an benefit over conventional methods.

Efficiency

With 3D printing, time savings occur due to the simplified process. Clinicians need not disinfect impressions, post them or wait for delivery. Scans are sent directly to the lab in minutes and model manipulation can be more efficient, with less trimming or processing. This results in time savings at each stage, so patients have less wait time between appointments. [15-17].

Reduced Lab fees

If the volume of printing is sufficient, then reduced lab fees can be achieved. This can mean cost to the patient is reduced, which increases the competitive edge of the practice over other orthodontists as well as general profitability [18].

One Machine, Multiple Products

Advancements in 3D-printing have improved printing quality, speeds, and material selection. Resins are designed for particular purposes, such as occlusal splinting, retainers, brackets and models, yet can all be used with the same printer. This allows for greater flexibility and customisation in treatment provision and negates additional machine investment.

Customisable Treatment

Every patient has a unique malocclusion that requires tailored treatment planning. 3D printing allows for completely customisable appliances. Recent case reports have presented appliances including distilisers, expanders and brackets (19).

Improved material properties

3D prints can have the same or better material properties than conventional methods, which improves the predictability of treatment [20]. In addition, resin models compared to stone models, are less prone to chipping and breaking .

Storage and organization

Less storage is required due to appliances being printed on a demand basis, freeing up office space for other purposes. Analogue models require large storage areas, and are subject to local laws on storage duration. The organisation can also cause problems, for instance delaying access to information. Digital storage increases efficiency via folders and labels allowing for quick searches of patients, scans and appliances [17, 21].

Improve Patient Experience

Unpleasant experiences can result from the taste of the impression material and may trigger gag reflexes. Scanning may reduce this and with properly trained staff can be completed quickly and efficiently, thus improving the patient experience. Wait times are decreased so treatment can be completed sooner and with fewer appointments, which enhances the patient's experience [18, 22, 23].

Disadvantages Of Digital Over Conventional Methods

Print Quality

Print quality depends on which printer is purchased, the materials chosen, and the various settings used when calibrating the printer. These variations can affect the quality and usability of the print [24-26].

Costs

There is a high initial cost due to printer purchase, software purchase and post-processing hardware. There is a possible need for replumbing, wiring and hiring a technician to handle the in-house lab [18].

Staff Training

An investment must be made into staff training which can be time-consuming and inefficient in the early stages. This can lead to increased errors in work, resulting in added appointments, loss of earnings and a poor patient experience.

All-in-one ecosystems (e.g. Formlabs and SprintRay) can overcome some of these downfalls. Slowly introducing 3D printing to the practice can allow familiarity and confidence before tackling bigger cases, i.e., initially only making retainers.

Another consideration is the doctor's time that might be required, which takes away from time with patients and other responsibilities.

Implementation

Changing routine systems in practice is challenging, requiring time, financial investment and staff encouragement in the new processes. Slow implementation can be helpful for the practice to adapt to new systems and protocols.

Ecological Effects

It is hard to recycle the waste material produced from 3D printing. In the early stages of incorporation of the technology, there is likely to be a high number of failed prints and increased wastage of resin. It is estimated that 20% of plastic can be recycled, of which 9% is recycled. Most of these will end up in landfill without being recycled (27). This increases the risk to the environment as well as health concerns of microplastics (28).

Furthermore, the IPA solution used in the washing process is dangerous to animal and aquatic life in high concentrations. IPA should never be placed down the drain as there can be ecological effects from the alcohol and the uncured resin (3). Therefore precautions must be taken for its correct disposal. A few methods of disposal include re-distilling the alcohol to separate the resin and allow for reuse or evaporation of the alcohol and curing of the residual resin.

Health and Safety

New technology in orthodontics must follow proper health and safety guidelines with regards to the use and storage of new materials (i.e., resins, IPA). Organisations such as EU-OSHA in Europe and FDA in the US have guidelines to help ensure the safety of staff and patients.

Insufficient Expertise

When deciding to 3D print, the practice becomes a manufacturer, which requires expertise in the process. Consideration needs to be made to staff expertise and training to in all stages of the process.

Space Requirements

Practices will need additional room for the 3D printers and post-curing processes. Additional wiring, venting and plumbing may be needed, which potentially could prevent having an additional chair in orthodontic practice (18).

Hardware Company Longevity

Researching the printer manufacturer to determine if they are industry leaders or a start-up company is essential. Printers are costly, and it is vital to research the warranties surrounding the printer in case the company goes into liquidation. Many new companies will start at a lower price while investment is sought after to retain new customers and then the price is increased after that, as this was the only option for company profitability in the long run. If the company fails and the printers have no warranties. New parts may be scarce, which would be detrimental to the practice.

Orthodontic applications

Models

One use is 3D-printing models for treatment planning as part of a multidisciplinary approach. Models, stents and guides can be produced allowing for final treatment mock-ups aiding in communication between labs and specialties. Many of these processes can save time by pre-measuring and completing analysis on CAD and 3D-printed models.

Occlusal splints and retainers

3D printing can be used for direct fabrication of retainers, which have demonstrated sufficient mechanical properties for function (29). In addition, models can be 3D printed and then retainers are made from these in the thermoforming process.

Occlusal splints can be easily designed on CAD software and printed, but special attention must be paid to the resin type. Different printing resins have different physical and chemical properties, and an occlusal splint requires adequate fracture resistance from occlusal loading (i.e. SprintRay NG flex). Each printer manufacturer has specific resins for

Aligner staging

Specific orthodontic CAD software can permit orthodontists to produce staging of in-house tooth movements for aligner production. Models are 3D-printed and then aligners are produced by vacuum forming around these models, or they can be printed directly [13, 30, 31]. Direct 3D-printed models are in their infancy and more research must be carried out to ensure comparable material quality to conventional methods.

Bracket printing

Customised 3D printed brackets can reduce the debond or fracture rate, improving patient experience and reducing chair time. Brackets can be fully customised to individual tooth morphology, helping transfer the appropriate torque onto the tooth and could potentially improve treatment outcomes [32, 33].

Virtual bracket removal

After orthodontic treatment, attachments and brackets must be removed before fabricating retainers. There is a risk that the teeth can relapse slightly in the time taken to receive the new retainers. Virtual bracket removal via CAD programming has shown to be equally as accurate for the clinical use of orthodontic retainers [34]. This method allows for instant debond and retainer fit, reducing the relapse risk.

Transfer brackets

Additionally, the transfer of brackets using transfer trays can be 3D-printed [35]. This is known as 'digital indirect bonding'. Conventionally these are placed on a cast model and then carefully placed over the teeth to ensure the brackets are positioned to provide the correct tension and torque for tooth movement. 3D printing can achieve this with reduced labour intensity and chair time. Moreover, this decreases saliva contamination when bonding the bracket, reducing debonding and improving accuracy over conventional methods [12, 36, 37].

Time and organization

3D printing can result in a faster turnaround due to fewer patient appointments and fewer steps in the process, saving chair time and allowing more patients to be seen [18]. CAD software allows labelling models and automatically placing aligner numbers to ensure the patient places the aligners in sequence.

Direct aligner printing

Direct aligner printing technology is in its early stages. Graphy was the first to develop a photocurable resin that would allow for direct aligner printing. CAD programmes (i.e. uLab, Delta Face) work by creating a 'shell' design for aligner construction. Retention can be controlled by blocking undercuts in the shell design, depending on the case needs. Lastly, support structures are required before printing because this shell design is more likely to distort.

More research is required to ensure the material characteristics are as effective as conventional thermoformed aligners. This technology will undoubtedly grow in popularity and accuracy as more development and research is carried out. Direct aligner printing will significantly reduce environmental waste and speed up manufacturing.

Orthognathic surgery

3D printing technology is used in orthognathic surgery. Currenlty, it can be used to print orthognathic wafers, cutting guides and models for treatment (Figure 8).

Band and loops

Conventionally, the band and loop system has been employed in orthodontic space maintenance to help with the early loss of deciduous teeth. However, there is a tendency for cement disintegration due to ill-fitting bands and increased chair time. 3D-printing technology allows the construction of personalised space maintainers, overcoming conventional methods' drawbacks [38].

Metal printing

Recent developments in the use of Selective Laser Melting (SLM) and Selective Laser Sintering (SLS) are being used to create metal appliances such as rapid palatal expanders (RPEs) and other metal-based appliances such as brackets/springs and screws. These processes are increasing the accuracy of appliances and the personalisation of individual treatment plans [39]. The printers are costly, and the current return on investment for practices favours the buying decision. This will change once cost and print time decrease [18].

Figure 8: *3D printed Surgical Stents.*

Return on Investment (ROI)

Choosing to invest in a 3D printer should be based on the potential for Return on Investment (ROI) These ROI calculators are provided from some leading manufacturers and can be used to determine investment potential.

There are two options when considering an item: purchase and produce. When purchasing an item, cost and quality are important factors. Cost is essential to working out the viability of 3D-printer investment, but also ensuring prints are of comparable quality to the purchased products.

Purchasing can be viewed as a fixed cost, whereas when producing an item, labour costs, material and running costs are combined to give a combined value [18]. For fabrication, costs are associated with printer purchase, washer/curer, software and scanner required for the digital process. Maintenance costs must be considered along with materials such as consumables, resin, and post-processing solutions. Costs associated with the possible recruitment of an in-house technician and the potential need for plumbing and re-wiring of the printer room need consideration.

Different objects will require individual calculation, due to the different sizes and volumes of prints. Smaller items, like brackets, will incur smaller 'per print' cost than larger items, such as models. Ortho-CAD software have features that can quantify the resin used and time for each print, allowing a cost per print to be calculated.

These costs must be combined to determine a 'break even' figure. This number signifies the minimum number of prints required to break even, which will help determine the purchase or produce debate. Table 1 demonstrates and example of this, with the cost of buying versus manufacturing clear aligners in the context of return of investment (ROI).

Table 1: Figures above are arbitrary numbers for illustration purposes.

Upfront Costs	In-House 3D Printing	Purchasing/ Outsourcing
Printer And Software Cost	£3000	£0
Training (Optional)	£500	£0
Material Costs	£100	£0
Cost Per Print	£10	£30
10 Prints	£3600 + £100 = £3700	£300
50 Prints	£3600 + £500 = £4100	£1500
100 Prints	£3600 + £1000 = £4600	£3000
200 Prints	£3600 + £2000 = £5600	£6000

Future advances, developments and issues surrounding 3D printing

Printer hardware

As 3D printing gains popularity, improvements will be seen in the printing quality and material levels. Printing-wise, printers will be able to print at greater speeds with increased accuracy and volume, while refined materials will have better properties (biocompatibility, environmentally friendly and less shrinkage). A greater level of personalised treatment will be achieved, even shade-matching brackets to teeth for patients who do not want clear aligners or lingual appliances [33].

Materials and the environment

Material selection has improved drastically and will only improve going forward. This will improve biocompatibility, mechanical strength and an increased printing range. As the world becomes more conscious of its carbon footprint and the need to protect the planet, new materials are being developed to ensure the technology becomes more sustainable.

In development now is the use of nylon in manufacturing orthodontic appliances. Nylon does not create chemical bonds during curing and can, therefore, be recycled into pellets. These pellets can then be used in the non-cosmetic part of cars and other machinery.

Brand monopolies

Another significant development is the specialist orthodontists' ability to challenge big brands with monopolies on clear aligner systems. By printing aligners, costs will decrease for the practice which can be reflected in the reduced cost to the patient. This event may encourage larger companies to improve their customer experiences, reduce their lab fees and add value to their products [40].

Conclusion

3D printing represents a pivotal facet of the evolving field often referred to as the fourth industrial revolution, encompassing not only hardware but also the encompassing software and digital workflows. The continuous advancement of this technology is propelled by substantial investments driven by commercial interests and bolstered by an expanding body of research validating its utility.

When executed with appropriate materials and adherence to printing protocols, 3D printing yields precise and durable dental models, circumventing the inaccuracies inherent in conventional dental impressions and plaster models. This transition from traditional fabrication methods to a fully digital workflow has been shown to yield cost savings and enhance overall operational efficiencies.

Accessible across a range of price points, 3D printing offers orthodontists flexibility in selecting comprehensive ecosystems or individual components and software. While turnkey solutions like SprintRay or Formlabs simplify the process at a higher cost, the alternative path entails more time and a deeper understanding of 3D printing. Practices considering 3D printing should conduct thorough return on investment assessments to determine its feasibility based on their specific needs.

With a discernible shift from analog to scanning and digital workflows, 3D printing emerges as the logical next step in this evolutionary trajectory. Its increasing accessibility and affordability, coupled with improved hardware and user-friendliness, position 3D printing as an integral component of many orthodontic practices in the near future.

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Declaration of Competing Interest

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

JS was responsible for the conceptualisation of the paper topic. JS, SH and JW were all involved in writing the original draft, editing and reviewing the manuscript.

References

1. Gottwald J, inventorLiquid metal recorder. USA1971.
2. Hull C, inventorApparatus for production of three-dimensional objects by stereolithography. USA1986.
3. Roberson GA, Sinha PK, editors. 3D printing in orthodontics: A practical guide to the printer technology and selection. Seminars in Orthodontics; 2022: Elsevier.
4. Cousley RR. Introducing 3D printing in your orthodontic practice. Journal of orthodontics. 2020;47(3):265-72.
5. Formlabs. Understanding accuracy, precision, and tolerance in 3D printing. 2023 [
6. Tsolakis IA, Gizani S, Panayi N, Antonopoulos G, Tsolakis AI. Three-dimensional printing technology in orthodontics for dental models: a systematic review. Children. 2022;9(8):1106.
7. Formlabs. Dental 3D printer price: How much does dental 3D-printing cost? 2023 [Available from: https://dental.formlabs.com/uk/blog/dental-3d-printer-price.
8. Javaid M, Haleem A, Kumar L. Current status and applications of 3D scanning in dentistry. Clinical Epidemiology and Global Health. 2019;7(2):228-33.
9. Kondo H. SLA post-processing: Best ways to clean your resin 3d prints 2022 [Available from: https://all3dp.com/2/sla-post-processing-best-ways-to-clean-your-resin-3d-prints/.
10. Brown GB, Currier GF, Kadioglu O, Kierl JP. Accuracy of 3-dimensional printed dental models reconstructed from digital intraoral impressions. American Journal of Orthodontics and Dentofacial Orthopedics. 2018;154(5):733-9.
11. Jindal P, Juneja M, Siena FL, Bajaj D, Breedon P. Mechanical and geometric properties of thermoformed and 3D printed clear dental aligners. American Journal of Orthodontics and Dentofacial Orthopedics. 2019;156(5):694-701.
12. Hoffmann L, Sabbagh H, Wichelhaus A, Kessler A. Bracket transfer accuracy with two different three-dimensional printed transfer trays vs silicone transfer trays. The Angle Orthodontist. 2022;92(3):364-71.
13. Maspero C, Tartaglia GM. 3D printing of clear orthodontic aligners: where we are and where we are going. MDPI; 2020. p. 5204.
14. Bakdach WMM, Hadad R. Linear and angular transfer accuracy of labial brackets using three dimensional-printed indirect bonding trays: A systematic review and meta-analysis. International Orthodontics. 2022;20(1):100612.
15. Bethany C, Jayda L, Sarah Y, Chengpeng C, Dana MS. Evaluation of 3D printing and its potential impact on biotechnology and the chemical sciences. Anal Chem. 2014;86(7).
16. Tian Y, Chen C, Xu X, Wang J, Hou X, Li K, et al. A review of 3D printing in dentistry: Technologies, affecting factors, and applications. Scanning. 2021;2021.
17. Dawood A, Marti Marti B, Sauret-Jackson V, Darwood A. 3D printing in dentistry. Br Dent J. 2015;219(11):521-9.
18. Layman B, Khosravi R, Sinha P, editors. Cost driven decision making on 3D printing appliances in-office. Seminars in Orthodontics; 2022: Elsevier.
19. Thurzo A, Urbanová W, Novák B, Waczulíková I, Varga I. Utilization of a 3D Printed Orthodontic Distalizer for Tooth-Borne Hybrid Treatment in Class II Unilateral Malocclusions. Materials. 2022;15(5):1740.
20. Hodecker L, Bourauel C, Braumann B, Kruse T, Christ H, Scharf S. Comparative in vitro analysis of the sliding resistance of a modern 3D-printed polymer bracket in combination with different archwire types. Clinical Oral Investigations. 2022;26(5):4049-57.
21. Christopoulou I, Kaklamanos EG, Makrygiannakis MA, Bitsanis I, Perlea P, Tsolakis AI. Intraoral scanners in Orthodontics: A critical review. International Journal of Environmental Research and Public Health. 2022;19(3):1407.
22. Impellizzeri A, Horodynski M, De Stefano A, Palaia G, Polimeni A, Romeo U, et al. CBCT and intra-oral scanner: The advantages of 3D technologies in orthodontic treatment. International Journal of Environmental Research and Public Health. 2020;17(24):9428.
23. Gardner S, Khosravi R, Detweiler M, Owen B, editors. 3D printing digitally planned in-direct bonding tray. Seminars in Orthodontics; 2022: Elsevier.

24. Venezia P, Ronsivalle V, Rustico L, Barbato E, Leonardi R, Giudice AL. Accuracy of orthodontic models prototyped for clear aligners therapy: A 3D imaging analysis comparing different market segments 3D printing protocols. Journal of Dentistry. 2022;124:104212.

25. Kenning KB, Risinger DC, English JD, Cozad BE, Harris LM, Ontiveros JC, et al. Evaluation of the dimensional accuracy of thermoformed appliances taken from 3D printed models with varied shell thicknesses: An in vitro study. International Orthodontics. 2021;19(1):137-46.

26. Zinelis S, Panayi N, Polychronis G, Papageorgiou SN, Eliades T. Comparative analysis of mechanical properties of orthodontic aligners produced by different contemporary 3D printers. Orthod Craniofac Res. 2022;25(3):336-41.

27. Bichu YM, Alwafi A, Liu X, Andrews J, Ludwig B, Bichu AY, et al. Advances in orthodontic clear aligner materials. Bioactive Materials. 2023;22:384-403.

28. Kandil S. Clear Aligners: A plastic economic bubble 2019 [Available from: https://www.kline-europe.com/post/zahnschienen-eine-wirtschaftsblase-aus-plastik.

29. Firlej M, Zaborowicz K, Zaborowicz M, Firlej E, Domagała I, Pieniak D, et al. Mechanical properties of 3D printed orthodontic retainers. International Journal of Environmental Research and Public Health. 2022;19(9):5775.

30. Tartaglia GM, Mapelli A, Maspero C, Santaniello T, Serafin M, Farronato M, et al. Direct 3D printing of clear orthodontic aligners: current state and future possibilities. Materials. 2021;14(7):1799.

31. Shivapuja P, inventorDirect 3d-printed orthodontic aligners with torque, rotation, and full control anchors. USA2023.

32. Polychronis G, Papageorgiou SN, Riollo CS, Panayi N, Zinelis S, Eliades T. Fracture toughness and hardness of in-office, 3D-printed ceramic brackets. Orthodontics & Craniofacial Research. 2023.

33. Yang L, Yin G, Liao X, Yin X, Ye N. A novel customized ceramic bracket for esthetic orthodontics: in vitro study. Progress in orthodontics. 2019;20:1-10.

34. Marsh K, Weissheimer A, Yin K, Chamberlain-Umanoff A, Tong H, Sameshima GT. Three-dimensional assessment of virtual bracket removal for orthodontic retainers: A prospective clinical study. American Journal of Orthodontics and Dentofacial Orthopedics. 2021;160(2):302-11.

35. Duarte MEA, Gribel BF, Spitz A, Artese F, Miguel JAM. Reproducibility of digital indirect bonding technique using three-dimensional (3D) models and 3D-printed transfer trays. The Angle Orthodontist. 2020;90(1):92-9.

36. Bachour PC, Klabunde R, Grünheid T. Transfer accuracy of 3D-printed trays for indirect bonding of orthodontic brackets: A clinical study. The Angle Orthodontist. 2022;92(3):372-9.

37. Shin S-H, Lee K-J, Kim S-J, Yu H-S, Kim K-M, Hwang C-J, et al. Accuracy of bracket position using thermoplastic and 3D -printed indirect bonding trays. International Journal of Computerized Dentistry. 2021;24(2).

38. Pawar BA. Maintenance of space by innovative three-dimensional-printed band and loop space maintainer. Journal of Indian Society of Pedodontics and Preventive Dentistry. 2019;37(2):205-8.

39. Barone S, Neri P, Paoli A, Razionale AV. Design and manufacturing of patient-specific orthodontic appliances by computer-aided engineering techniques. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine. 2018;232(1):54-66.

40. Cousley RR. In-house three-dimensional printing within the digital orthodontic workflow. Journal of the World Federation of Orthodontists. 2022;11(6):182-9.

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