

Histo-anatomic 3D printing of dental structures

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In brief

Learn about the key to digital aesthetics.

Learn about the advantages and potential of tooth-structure databases.

Learn about the next generation of manufacturing devices for CAD restorations

The creation of dental restorations with natural appearance and biomechanics represents a major challenge for the restorative team. The manufacturing-process of high-aesthetic restorations from tooth-coloured restorative materials is currently dominated by manual manufacturing procedures and the outcome is highly dependent on the knowledge and skills of the performing dental technician. On the other hand, due to the simplicity of the manufacturing process, CAD/CAM restorations from different material classes gain more and more acceptance in the daily routine. Multi-layered restorations show significant aesthetic advantages versus monolithic ones, but are difficult to fabricate using digital technologies. The key element for the successful automated digital fabrication of aesthetic anterior restorations seems to be the form of the individual dentine core as defined by dentine enamel junction (DEJ) covered by a more transparent layer of material imitating the enamel layer to create the outer enamel surface (OES). This article describes the possibilities and technologies available for so-called '4D-printing'. It introduces the digital manufacturing process of multilayered anterior teeth using 3D multipart printing, taking the example of manufacturing replicas of extracted intact natural teeth.

Introduction

Manufacturing of high-aesthetic restorations from tooth-coloured restorative materials is currently dominated by manual manufacturing procedures and the aesthetic outcome is highly dependent on the knowledge and skills of the performing dental technician and the mastering of the '2D-3D-4D approach' to dental morphology.¹ Due to this the highly technique-sensitive procedure that needs a considerable amount of experience, several steps are often necessary to achieve pleasing aesthetic outcomes.

In all fields of industrial fabrication additive manufacturing processes currently arouse great interest. In the dental field, additive approaches

have been applied already for more than one decade, such as the stereo-lithographic manufacturing of implant-drill-guides for guided surgery-procedures and laser-sintered alloys, which have paved the way for additive fabrication technologies in dentistry. Nowadays, even the full digital workflow, starting with intraoral-scanning, requires the use of computer-aided manufactured physical models on the basis of digital data. Consequently, additive technologies are increasingly used, especially stereo-lithography, laser-sintering and 3D-printing, as well as digital light processing (DLP).

Until recently, mainly monolithic restorations have been used in dentistry. Since 2014, printers have been capable to process multiple materials in one single manufacturing cycle. This enables new approaches for dental applications. Especially the combination of 3D-multipart and multicolour printing, allowing the relentless pursuit of the biomimetic emulation of teeth.² In this regard, a key element for the optical integration and aesthetic appearance of dental restorations is the thorough understanding of the histo-anatomic structures and dynamic light interaction of the natural dentition.³ Especially

the tri-dimensional form of the dentine core, as defined by the dentino-enamel junction (DEJ) and the sigmoid curve distribution (convex enamel/concave dentine) seem to be decisive for the optical appearance of a tooth and a restoration respectively.⁴ The DEJ and the outer enamel surface (OES) are essential three-dimensional structures of the tooth that substantially influence its optical appearance (Fig. 1).

Hence, a prerequisite for the so-called '4D-printing' (multi-layered 3D-printing) of teeth or dental restorations are tooth-structure databanks containing the three-dimensional information about the outer and also inner architecture of natural teeth. Such databanks already exist and are patented including connected technologies.^{5,6} Those databanks mean the basis for 3D multi-material printing of teeth and restorations respectively. The tooth structure databank is loaded with several datasets for each tooth (OES, the DEJ and pulp geometry).

The DEJ may contain significant information about the outer surface of a tooth.⁷⁻¹⁷ Inversely, this might allow to determine the inner architecture (DEJ) from the outer surface. Furthermore, outer and inner layer-geometries

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may be dynamically connected to each other. This implies that virtually modifying the outer surface of a tooth in the CAD-software would automatically lead to an alteration of the corresponding inner structure.^{5,6,18} One basic challenge in this approach is the capturing of the inner structures of each type of intact natural tooth, in order to learn more about the specific relation of DEJ and OES.

This article describes possible technological approaches to: 1) capture and digitise the outer and inner structure of human teeth; and 2) print natural-looking teeth and dental restorations. The digital manufacturing process of multi-layered anterior teeth using 4D-printing will be demonstrated by manufacturing physical replicas of extracted intact natural teeth.

Description of technology

3D capturing of outer and inner tooth-structures

Digitising and displaying the outer and inner tooth-structures three-dimensionally, especially the DEJ, can be currently achieved using hybrid analogue-numerical or numerical-only techniques. Additional technologies will be presented that might be able to capture the inner tooth structure in a near future but are still under development.

Analogue-numerical capturing – chemical removal of enamel and 3D-digitalisation

A destructive method used in the 1950s and 1960s to expose the DEJ was the chemical removal of the enamel layer using 37% phosphoric acid.^{8,19} Before this irreversible loss of the OES, it first needs to be captured by conventional impressions or nowadays digitally by scanning the crown with mechanical (for example, Procera forte, Nobel Biocare, Sweden), light optical lasers – or stripe-light-based detectors. After the chemical removal of the enamel layer the same technologies are used to scan the exposed dentine core.

Digital capturing – computed tomography/ cone beam computer tomography

The numerical capturing of the three-dimensional geometry of the OES and DEJ can be conducted by X-ray methods using computed tomography (CT) or cone beam computed tomography (CBCT).^{20–22} The resolution and accuracy can vary significantly between the systems. This might lead to limitations in receiving data with sufficient accuracy and resolution for further processing. Using 3d

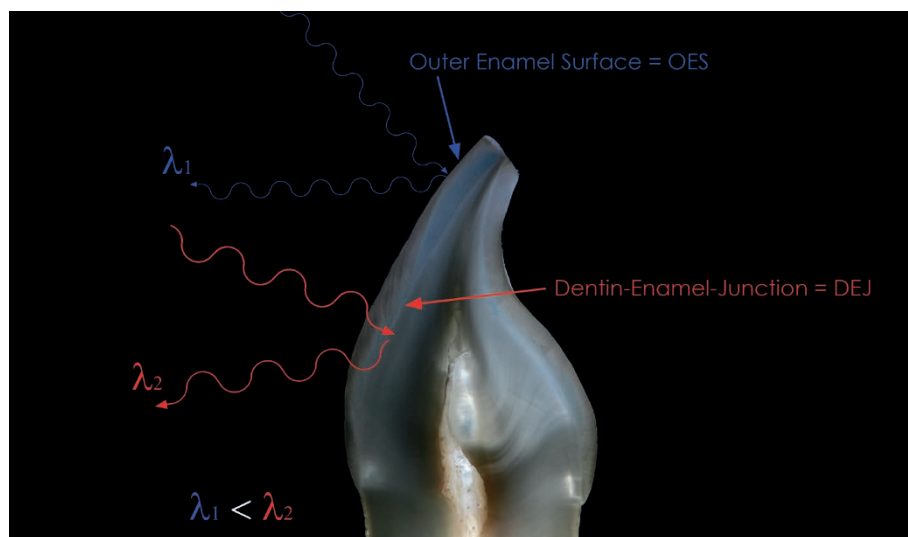


Fig. 1 Dentine enamel junction (DEJ) and outer enamel surface (OES)

data-processing software two-dimensional data from the CBCT are converted into DICOM-data (DICOM = digital imaging and communications in medicine) as a first step. Subsequently STL-data (STL = Standard Tessellation Language) for each inner structure can be generated from the DICOM data based on the voxel density of the different (human) tissues using a segmentation software (for example, Mimics, Materialize, Belgium etc).

Digital capturing – micro computed tomography

The most accurate data of the OES and DEJ can be generated using micro-computed tomography technology.²³ Although a better resolution than with CT and CBCT can be achieved, the technology cannot be used *in vivo* due to the radiation level. This limits its application to extracted or cadaver teeth. This technology was used to digitise the teeth that were used as a reference template for the 3D-mult-material printing approach that is described hereinafter.

Future acquisition perspectives – ultrasonic acquisition

A further physical acquisition method for inner tooth structures is based on ultrasonic technology. Within the frame of a scientific research project at the Rheinisch-Westfälische Technische Hochschule Aachen (RWTH, Germany) an ultrasonic-based acquisition device is under development.^{24,25} Because acoustic waves penetrate gingiva, saliva and blood, tooth areas below the gingiva can be detected and captured without invasive resection. Further on, the scanner can capture

the surface of prepared teeth, as well as the outer enamel surface (OES) of intact teeth. Due to the underlying physical principle of the ultrasonic acquisition it might be also possible to acquire deeper layers of natural teeth, like the DEJ.

Future acquisition perspectives – light-optical acquisition

Most of the current 3D intraoral scanning devices are based on light-optical principles.

Within this group systems based on the triangulation principle and systems with parallel light projection can be distinguished. Using the triangulation principle, structural light or non-structural light can be used. Stereophotogrammetry works without structural light, whereas in laser-light-cut and stripe-light-scanners a light-projection is used.

In addition, so-called 'stochastic patterns' can be applied during light-projection. Enamel is transparent for light with long wavelengths. Therefore, this kind of light penetrates and is reflected at the DEJ, whereas light with shorter wavelength is reflected right at the OES^{26,27} (Fig. 1).

The optical coherence tomography (OCT) is a diagnostic method for cross-sectional imaging of internal biological structures. It is actually an interferometric technique, which uses infrared light waves that reflect off the internal microstructure in a way that is principally comparable to an ultrasonic pulse echo.²⁸ The technology of optical coherence tomography was first described by Fujimoto *et al.* in 1991.²⁹ Otis *et al.*³⁰ presented the first *in vivo* OCT images of human dental tissues and Feldchtein *et. al.*³¹ showed that the

dentine-enamel-junction (DEJ) can be. High transversal and depth resolution (up to 10 µm) can be obtained, but one of the current problems seems to be the insufficient penetrating depth.³²

Transillumination of teeth has been already applied for several years in the field of caries detection, especially to detect cracks and fractures of dental hard tissues. One example is digital imaging fiber optic transillumination (DIFOTI). Since 2012 a further development of the DIFOTI-System, the DIAGNOcam (KAVO, Biberach, Germany) is available. A light of long wavelength (740 nm, near-infrared) is applied to the lingual and buccal surfaces of the tooth, bone and root. The light is scattered in all directions including the coronal direction. A CCD-sensor sensible for near-infrared light, positioned over the occlusal surface, captures the image. The long wavelength enables the penetration of the gingiva, bone and tooth tissue. As a result, the enamel is displayed transparent and the DEJ can be recognised clearly.

The combination of near-infrared-transillumination (780 nm up to 1,400 nm) and an intraoral 3D scanner, based for example on photogrammetry, might enable to detect the DEJ three dimensionally and export the information as a '4D' dataset.

Overview of additive manufacturing

In common usage the expression '3D-printing' is often used as a hypernym for all additive manufacturing technologies and procedures. However, technically, the expression is only used for fused deposition modeling (FDM). A distinct classification of additive manufacturing processes is described in the ISO-guideline No. 17,296, which categorises the additive technologies (Rapid Prototyping [RP]-technologies) into two major groups.³³

Binder jetting

With binder jetting methods the object is built layer by layer – each layer of material (liquid, powder, solid) being placed onto a platform. The binding agent is selectively deposited to join powder particles appropriately in accordance to the contours of the object to build. The following technologies are among the binding methods:

- Stereolithography (SLA)
- Selective laser sintering (SLS)
- Indirect 3D-printing (powder bed printers)
- LOM-Technologies (laminated object manufacturing)

Material jetting

In this deposition method, the material is dispensed through a nozzle or print head continuously or in single drops and placed layer by layer as a point or line-pattern.

- The following technologies belong to this group:
- Fused deposition modeling-technologies (FDM)
- Direct 3D-printing
- 3D-material-extrusion of pastes
- Polyjet-technologies, where photo-sensitive polymers are placed drop-like over a print head.

General description of the workflow using additive manufacturing technologies

In general all additive technologies are following the same workflow including the following steps:

Computer aided design (CAD) of components

During the CAD process the virtual design of the object is conducted in specific software. Subsequently to the CAD process, the construction dataset can be saved in different possible formats. Mostly the STL-format is used, which describes the surface of the object with the help of multiple small triangles.

Slicing of the CAD dataset

With the help of another software, for example, Objet Studio (Stratasys, Eden Prairie, MN) or CAMbridge, (3Shape, Copenhagen, DNK) the STL dataset is sliced into single layers similar in thickness.

Layer-by-layer buildup of the object in accordance to the 'sliced' data

On the basis of the sliced STL dataset the object is built layer-by-layer. The accuracy in the direction of buildup (Z-axis) is mainly dependent on the thickness of each single layer. The single layers are always visible in the resulting object. Even with high resolution, thin slices and high precision of the outlines, thin striations remain recognisable and lead to a rough surface of the object, which might require a post-processing surface polishing. This undesirable effect is called Z-stepping.

Multi-layered dental structures

The technology: multi-material 3D printing

Printing dental restorations by additive manufacturing with different materials of different

properties and colours is now possible in one build-up process called 'multi-material-3D-printing', which could be simplified as '4D printing'. This technology makes processes that were conducted so far in multiple steps or assemblies, achievable in one single process.

In the meantime several manufacturers of additive manufacturing systems offer this technology. Here FDM-technology, as well as direct and indirect 3D-printing (powder) is applied. Current examples of direct multi-material 3-D-printers are PolyJet-3D-printing (Stratasys), MultiJet-Printing (MJP; 3D Systems) and MultiJet Fusion-3D-printing (Hewlett Packard).

Within the group of indirect multi-material-printers, WZR-Multimaterial-3D-printing (WZR ceramic solutions GmbH, Rheinbach) is the only system available. This procedure is patented by WZR.

3D multi-material-printing of replicas of natural teeth

The following section describes the digital manufacturing process of multilayered anterior teeth using 3D multi-material-printing. Replicas of extracted intact natural teeth were produced and subsequently evaluated.

For the acquisition of datasets, extracted teeth were scanned using micro-computed tomography (exaCT S Desktop-CT S60 HRE; Wenzel Volumetrik GmbH, Singen, D) with a voxel-size of 45 µm. The acquisition software 'exaCT Control Analysis' (Wenzel Volumetrik GmbH, Singen, D) was used to generate STL-data of the enamel (including OES and DEJ), as well as data of the dentine core including the root and pulp cavity (Fig. 2).

The post-processing of the data, especially the optimisation of the surface quality used the software Sensable Freeform (3D Systems, Rock Hill, US). Dependent on the individual situation the 'natural blueprint' might be manually altered using existing CAD-software.

In the next step the STL-data were analysed with the software Magics RP (Materialise, Leuven, Belgium), to detect and eliminate possible errors within the dataset, that could negatively influence the structure and homogeneity of the future object. The positioning of the teeth on the printing platform and the slicing of datasets was obtained with the software Objet Studio (Stratasys, Eden Prairie, MN).

On the basis of the sliced datasets the teeth were additively build up using the direct-3D-printing-system 'Objet260 Dental Selection' (Stratasys). The Objet260 Dental Selection is the most current 3D dental printer with

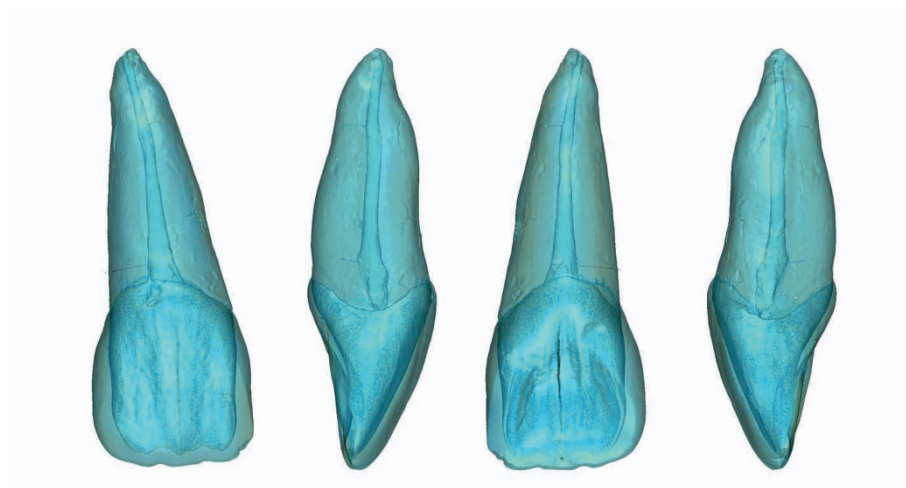


Fig. 2 STL-data of multi-layered structure (DEJ and OES) of a natural upper incisor extracted from DICOM datasets generated by micro-computed tomography (Micro-CT). These data were used as form-models for 3D-replication by multi-material 3D-printing

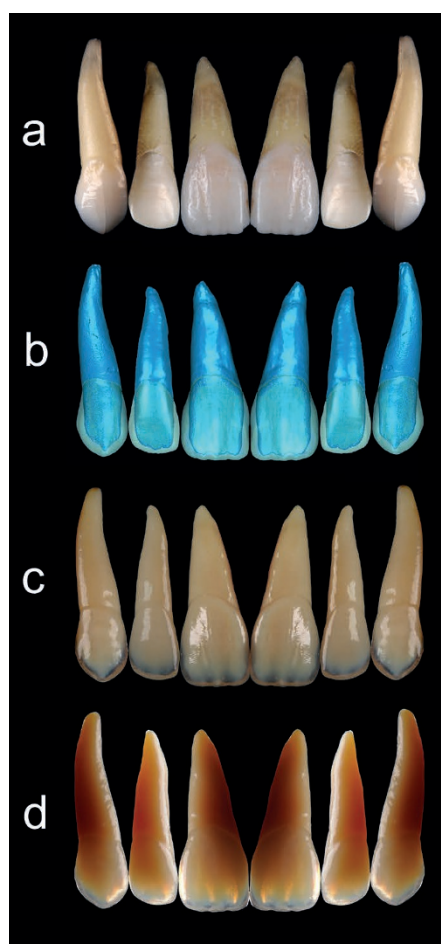


Fig. 3 From natural tooth to 3D-printed replica: a) extracted natural upper anteriors; b) STL-data of DEJ and OES filtered from micro computed tomography; c) 3D-multi-material-printed replicas of natural teeth (incident light); d) 3D-multi-material- printed replicas of natural teeth (transmitted light)

triple-jetting-technology. Realistic colours as well as detailed surface structures can be printed with three different materials in one process.

Applied materials

Dentine core

For the root and dentine-core the material 'Objet VeroGlaze MED620' was used in shade A2. This material exhibits sufficient strength and form stability and a translucency comparable to natural dentine. VeroGlaze is currently approved for temporary intraoral application of maximum 24 hours. Therefore it can be applied for diagnostic try-ins and mock-ups.

Incisal area

The incisal area was printed using the transparent and strong material 'Objet MED610 Biocompatible, Clear'.

Both materials were printed simultaneously. For the outer surface, an automatic surface finish was used with the so called 'glossy-mode', which enabled to create a clear finished surface on the object. This is only possible on surfaces that are not affected by necessary support structures. Therefore, the object to be printed has to be positioned in the right direction on the platform. The remaining surfaces facing the platform (where the support structure touch the object) stay with a mat finish

Evaluation of printing results

The first results seem very promising. Evaluation included the 'aesthetic appearance' and the 'surface quality'.

The aesthetic result can be described as excellent. The additively produced teeth show

light dynamic effects that are similar to those seen in the natural model teeth. They are likely caused by the scattering of the light on the dentine-core, leading to several specific effects in the incisal area. The three-dimensional form of the dentine-core therefore has instantaneous influence on the overall aesthetic result of the printed teeth.

Due to the nature and organic optical behaviour of the materials used (resins), it can be assumed that beautiful biomimetic reproductions of teeth can be generated with a very simple build-up scheme and a simple bilaminar approach (dentine and enamel) (Figs 3a–d). Under incident and transmitted light the printed teeth show extreme light dynamics that are even more pronounced than in natural teeth.

In the feasibility study, the buccal surfaces of the anterior teeth were positioned upwards with regards to the build-up direction. Therefore, the tooth surface exhibited different qualities, as the most upper surfaces were produced in glossy-mode. These surfaces showed a very smooth, homogeneous and shiny surface, whereas the side and lower surfaces showed a rougher surface with z-stepping, due to the supporting structures. This shortcoming can be easily resolved by manual finishing using silicone polishers (Silico, Heraeus Kulzer, Hanau) and natural bristle brush with polishing pastes (Acrypol and Abraso Starglanz, Bredent, Senden) even though the degree of gloss was superior in the automatically generated 'high-gloss' areas.

Discussion

The presented procedure enables to manufacture multi-layered artificial 'teeth' or dental restorations in one single manufacturing process on the basis of natural tooth structure databases. This makes the production fast and reproducible. The costs for the print-process itself can be considered economically, however the 3D printers are still expensive. The printed objects with their multi-layered structure have optical behaviour that even supersedes to their natural model. Because the aesthetic appearance is predictable, even dental technicians with limited skills in manual layering-techniques might be able to achieve good and predictable aesthetical results.

In addition, the manufacturing-effort is considerably simplified compared to all other known manufacturing approaches for multi-layered restorations (manual layering

technique, overpress-technique and digital veneering technique using multi-layer-technology like IPS e.max CAD-on).³⁴

The manufacturing of multi-layered crowns and bridges using a computer-numerical-control (CNC)-technique on the basis of tooth structure databanks has been described by the same authors as an alternative to 3D-multi-material-printing.¹⁸ The results can be deemed acceptable. The advantage of the subtractive manufacturing technique is that materials with proven clinical performances are used. However, the effort of subtractive manufacturing is significantly higher. Also when the dentine core exhibits undercuts it is impossible to mill a fitting outer part. This again speaks for the simultaneous build-up by additive approaches.

A current drawback of additive materials is that the photopolymers have only been approved for intraoral use for only 24 hours. According to the manufacturers website (www.stratasys.com) the materials have been tested only on irritations. The medical accreditation regarding cytotoxicity, genotoxicity, typ-4 hypersensitivity, as well as USP class 6 will follow in future. The mechanical properties of those resins are also inferior compared to those of resin-based materials used for definitive restorations. For example, the flexural modulus of the printed materials (MED 610 and MED 620) is about 2,200–3,200 MPa, whereas LAVA Ultimate (3M-ESPE, St. Paul, MN), a resin-based material for definitive CAD/CAM restorations exhibits a flexural modulus of 10,800 MPa.³⁵ The flexural modulus polymers applied for denture bases (IvoBase, Ivoclar Vivadent, Schaan, FL) is in the range of >1,500 MPa.³⁶ The flexural strength of denture base-materials (>60 MPa) is in the range of the printed resin material. In other words, the mechanical properties are similar to analogue PMMA-materials for removable denture base fabrication. One manufacturer has obtained the official FDA approval for printed denture bases, but it is based on a different additive technology (SLA).³⁷

Currently, the 24-hour use is sufficient for an aesthetic evaluation of the planned restoration in the form of a mock-up. Additionally to conventional mock-up methods, the new approach enables to evaluate the optical effects produced by the inner structure of the restoration intraorally. After successful evaluation, the dental technician can transfer the individual layering/3D-buildup into the definitive restoration. Due to the current limitations regarding the materials, the application of printed objects as temporary or definitive restorations is not yet possible.



Fig. 4 Display of STL-dataset of outer and inner tooth structure with 3D-multi-material printed 4-unit FPD in transmitted (middle) and incident light (right)



Fig. 5 4D-multi-material printed 4-unit FDP *in situ* for short-term try-in

Future material developments can be expected, both polymers and ceramics with appropriate stability in the oral environment. The biocompatibility of restorations fabricated with the subtractive approach from extremely homogeneous blocks stands as a golden standard and benchmark for future 3D-printed restorations.

3D multi-material printing on the basis of a tooth structure database would enable the user to have access to numerous tooth forms including their individual inner structure and therefore to achieve reproducible results. Finally, it should be possible on the basis of the databank to conclude (to infer) the shape of the inner 3D-structure of the dentine core from the digitally captured outer surface. This future research could establish a possible correlation between OES and DEJ. The three-dimensional capturing of the outer and inner layers, with special respect to the DEJ, will certainly be one of the great future tasks in the further development of intraoral digital capturing devices. Because conventional impression methods are not able to fulfil those requirements, only digital scanning technologies will bring possible solutions. Consequently, this means a unique characteristic of future digital impression devices.

Case study

This work represents the first proof of concept and practical application of the described workflow. Furthermore, a 4-unit-FPD was designed on the basis of this concept (Fig. 4). The restoration was printed using multi-material 3D-printing technology. Placing the printed FPD into the mouth enabled the restorative team to evaluate the outer form and also the individual three-dimensional layering of the future restoration (Fig. 5). Due to the fact that there is only a 100% clear material (MED 610) available to print the enamel layer, the incisal edge still appears unnaturally transparent. In spite of this, the first use of this technology and workflow points to a promising future.

Conclusion

The histo-anatomy of the tooth implies that dentine-core is the key to CAD/CAM-generated anterior-aesthetics. It is paramount in creating databanks with individual 3D tooth structures, including the outer tooth geometry (OES) as well as the inner dentine cores (DEJ). This will enable a completely new approach to digitally-generated restorations of anterior teeth.

Based on this concept and a first case study, it can be anticipated that a bilaminar technique simulating dentine and enamel structures three-dimensionally is appropriate to achieve acceptable aesthetic results. A key-element for future developments is the non-destructive acquisition of the natural structure of a dentine-core from adjacent or former teeth of the patient.

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