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CLINICAL ARTICLE

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Application of 3D-printed colored 3D-models for the fabrication of full ceramic restorations: A technical report

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Abstract

Objective: This paper presents a novel digital workflow that expedites and facilitates the manufacturing of high-end full-ceramic restorations based on "Print and Press"-Technology combined with 3D-printed colored 3D-models.

Clinical considerations: Despite ongoing innovations and developments in the digital workflow, the precision, and the final esthetic outcome is still limited compared with conventional press ceramics. The proposed method combines the advantages of digital scan- and design technologies with the proven conventional press-technology to accomplish high-end full-ceramic restorations. The restoration is digitally designed, the data set is 3D-printed in resin that can be burned out, subsequently conventionally embedded and pressed. Final esthetic finishing of the partial restorations is done on a 3D-printed physical colored 3D-model.

Conclusion: The report describes synergetic effects of digital and analog procedures. 3D-printed colored 3D-models can positively support the manufacturing of full ceramic restorations regarding their optical integration. Therefore, the use of 3D-printed colored 3D-models signifies a new innovative technique with many promising application areas.

Clinical significance: The combination of excellent clinical long-term data for pressed ceramic restorations and proven digital processes, like intraoral scanning, design, and additive manufacturing, in the dental field promise an individual workflow for predictability and excellent esthetics.

KEYWORDS
3D-models, 3D-printing, additive manufacturing, intraoral scanning, model builder software, print and press

1 | INTRODUCTION

The success of any restorative rehabilitation is based on implementing the correct information derived from the patient's oral situation. The digital workflow opens new ways of transferring this data predictably and efficiently from the dental practice to the dental laboratory. The first intraoral scanners (IOS) just captured the three-dimensional (3D) geometry of the maxilla and mandible associated with their relation but obtained no additional data. Over the years, technological developments have increased, particularly the accuracy and handling of digital impression devices.[1–5]

Today, several IOS are capable of recording color, surface, and tooth structure information digitally in accurate, reliable, and repeatable workflows.[6–10] Besides having this information available in the computer-aided design (CAD) software, the Polyjet technology, a 3D-material jetting process, offers a way to convert this data into true-colored physical models. Since the transfer of color information is not achievable with analog impressions, 3D-printed colored 3D-models seem to be a genuine "killer application" in manufacturing fixed restorations.

In recent years, a trend from subtractive to resource-saving additive manufacturing has been underway.[12] Some of those 3D-printed innovations are promising but still in the prototype phase for universal clinical application, for example, 3D-printed complete removable dental prostheses[13] or histo-anatomic 3D multipart printing considering outer and inner tooth layers for fixed restorations, so-called 4D-printing.[14] Others are already well established in the dental field. Examples are 3D-printed monocolored 3D-models based on 3D-data from IOS, occlusal splints, surgical templates (drilling guides), or individual impression trays.[12,15–19]

However, additive processes are also feasible to manufacture dental restorations. Laser sintering of CoCr crowns and bridges is used successfully[20] but does not meet the requirement of tooth-colored, esthetic restorations. For these, pressed ceramics or subtractively manufactured ceramics are still state of the art.[21–24] CAD-CAM technology, in particular, has expanded the product range of manufacturers enormously, especially for use in single-tooth restorations.[21,24] With the correct selection of the restoration material, a harmonious result can be achieved depending on the individual circumstances.[22,23,25] In addition to 3D-printable provisional tooth-shaded restorative materials, the first 3D-printable ceramically reinforced hybrid material for definitive single crowns has yet been approved for definitive restorations (e.g., Varseo SmileCrown^{plus}; BEGO, Bremen, Germany).[26] Although long-term data is not yet available, additive manufacturing appears to have great value in fabricating indirect restorations. On the contrary, no market-ready applications are yet available for direct 3D-printing of definitive ceramic restorations.[16] The most advanced method is possibly the patented Lithography-based Ceramic Manufacturing (LCM) process by Lithoz GmbH (Vienna, Austria).

Against that background, a current promising approach is to combine the digital and conventional workflow instead of relying entirely on one path. The described process here combines the advantages of digital design with the efficiency of 3D-printing[12] and proven ceramic pressing technology.[22,23] From this point forward, an innovative hybrid workflow could be established that links the IOS, additively manufactured colored 3D-models, and digitally designed but pressed ceramic restorations. Innovative possibilities could emerge associated with further enhancements and simplified procedures, especially for full-ceramic dental restorations.

This report presents a novel digital workflow that expedites and facilitates the manufacturing of high-end full-ceramic restorations based on "Print and Press"-Technology combined with 3D-printed colored 3D-models (Figure 1).

2 | APPLICATION OF CONCEPT

2.1 | Intraoral scanning systems

The 3D-data of the oral situation is acquired using intraoral scanners, which either apply the triangulation principle or the confocal laser beam principle. From the resulting 3D-point cloud a surface data set is generated primarily using triangular facets (e.g., standard tessellation language = STL). Both technologies also offer the possibility of capturing geometry-related color information (Figure 2). 3D-geometry information and color information have different file formats, for example, DCM, PLY, or OBJ files. The overall optical impression coding is usually based on RGB color space, which assigns an RGB triple to each point of the 3D-surface via a pixel image. This type of coding is similar in the file formats commonly used for 3D-printing, such as the OBJ or PLY format. In general linguistic use, the term "overall optical appearance" is usually reduced to color. In dental applications, however, six essential factors influence this "optical appearance" of an object:

- Color
- Translucency
- Shine
- Surface texture
- Fluorescence
- Opalescence

The first step of using the application is to scan the intraoral situation of the patient. Hence, it is essential to use an IOS the with ability to capture color information associated with the 3D-geometry

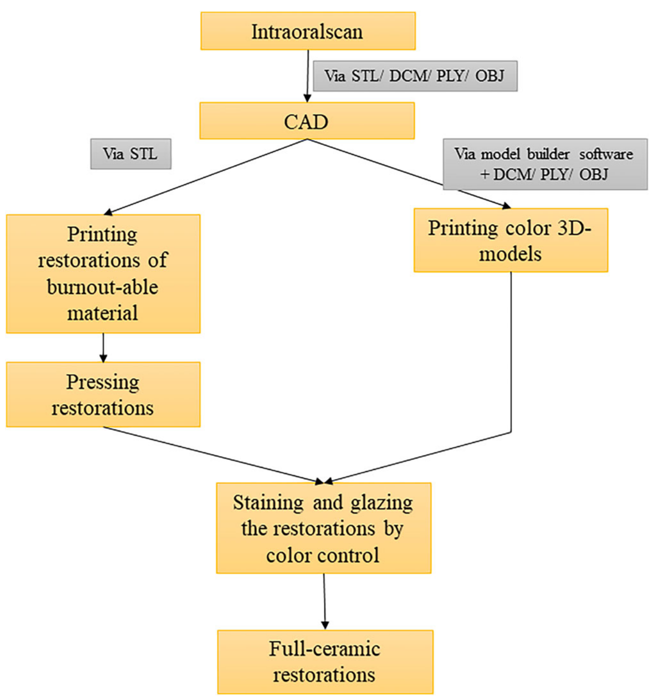

FIGURE 1 Schematic workflow of the concept

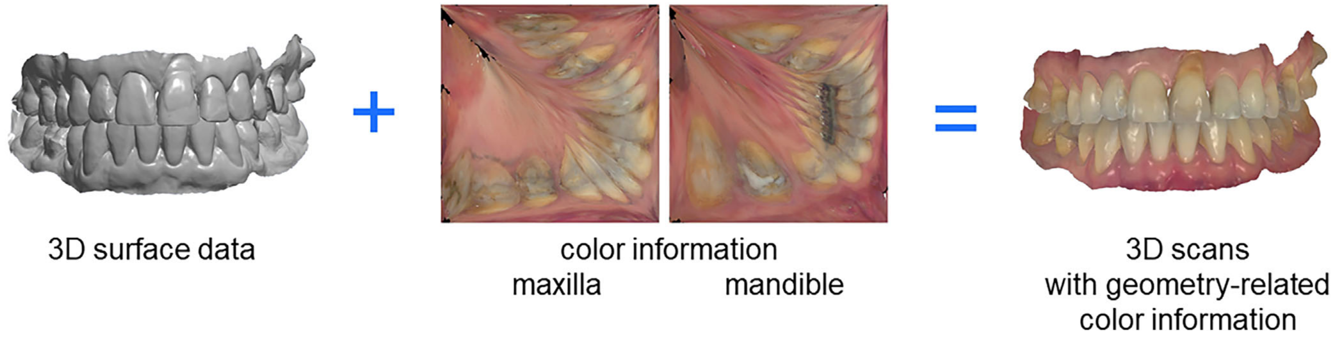

FIGURE 2 The surface data from intraoral 3D-scans of maxilla and mandible, combined with the color information, resulting in 3D-scans with geometry-related color information

(Figure 3) and to transfer the data into the CAD software. This dataset is the basis for manufacturing a restoration and model.

2.2 | Digital data preparation and 3D-printed colored 3D-models

In additive manufacturing, the term "graphic-3D-printing" refers to the area mainly concerned with the optical properties of 3D-printed products. Furthermore, three sub-areas can be distinguished: 3D-scanning, data processing, and data output using 3D-printers.

Data preparation is made using so called model builder software (in the present paper: Model Builder software, Dental System 2020 V20.1; 3Shape, Copenhagen, Denmark) to generate a virtual colored model, which is then converted into a physical colored model using multimaterial 3D-printing (Polyjet technology; Stratasys, Eden Prairie, MN, USA). The DCM data out of the CAD-software need to be converted into VRML file format to receive compatible data for the color 3D-printing process. The color information is geometry-related, that is, the two-dimensional (2D) color information is clearly assigned to the 3D-surface.

2.3 | 3D-printing of the colored 3D-models

Currently, different 3D-printing technologies enable the production of 3D-models. The most frequently applied VAT-photopolymerization technology (e.g., stereolithography (SLA) or "Direct Light processing" (DLP)) can print conventional monocolored models. A suitable technology for colored 3D-models is the so-called "powder bed 3D-printing" (binder jetting), in which differently colored binder liquids are injected into a powder bed. Thus, the component is solidified, and the color of the 3D-printed object is defined.

Nevertheless, material jetting (MJ) has opened entirely new possibilities to produce dental components, that is, colored 3D-models. Several manufacturers now offer this process, such as Stratasys (Eden Prairie, MN, USA), Mimaki (Nagano, Japan), Hewlett Packard (Palo Alto, CA, USA), and 3D-Systems (Rock Hill, SC, USA). The production of colored 3D-models is also possible using DLP, material extrusion, or sheet lamination. However, material jetting is currently used in the dental sector to deliver colored 3D-models.

By using Polyjet technology, that is, material jetting process (Polyjet technology, Stratasys; Eden Prairie), the colored physical master models with plug-in stumps (so-called "Geller stumps") were printed. Full-color 3D-printing of the master models was carried out using a Stratasys J850 Pro (printed at 3D Medical Print KG, Lenzing, Austria) (Figure 4). This multimaterial 3D-printer can display up to 500,000 colors with new different base materials using the polyjet process. By means of the so-called "glossy mode", a very smooth surface is achieved on the occlusal side. Non-glossy parts of the models are coated with a brush and the light-curing sealing varnish Palaseal (Kulzer GmbH, Hanau, Germany) and then cured in the high-performance light polymerization unit Uni XS (Kulzer, Hanau).

FIGURE 3 3D-intraoral scans (TRIOS 4; 3Shape, Copenhagen, Denmark) with patient-related color information to fabricate inlays and partial crowns in maxilla and mandible

2.4 | Fabrication of the restorations

Generally, restorations can be manufactured by analog means based on an existing physical model or entirely digital. However, to make optimum use of the digital workflow, it is advisable to design the restorations using CAD digitally. The inlays and partial crowns are designed in a CAD software (Modellier; Version v.6173_6843_x64; Zirkonzahn, Gais, Italy) (Figure 5) and exported as STL files. Subsequently, these restorations are imported into the DEKEMA trixCAD software (DEKEMA Dental-Keramiköfen GmbH, Freilassing, Germany). The restorations, including the placeholder for up to three pressing plungers, are positioned virtually on the muffle former (Figure 6). After calculating the individual layers (=slicing), the data are sent to the 3D-printer (DEKEMA trixprint; DEKEMA Dental-Keramiköfen GmbH, Freilassing). Then, the sliced layer data are printed from a 3D-printable resin that can be burned out, onto the base plate of the trixpress muffle system (DEKEMA trixprint; DEKEMA Dental-Keramiköfen GmbH, Freilassing). After 3D-printing, the components are cleaned and post-processed. Investing is carried out in the usual way using commonly available investment material. After heating the preheating furnace and a residue-free burnout, the press ceramic blanks are inserted into the muffle and pressed with the trixpress plungers (DEKEMA Dental-Keramiköfen GmbH, Freilassing, Germany) (Figure 7). The project-specific press program, calculated by the trixCAM software (DEKEMA Dental-Keramiköfen GmbH, Freilassing, Germany), has already been sent online to the Austromat 645i press ceramic furnace (DEKEMA Dental-Keramiköfen GmbH, Freilassing, Germany) for the pressing process. Alternatively, the data can also be transferred via a customary USB stick. After the pressing process, the inlays and partial crowns are separated from the press sprue and finalized by the familiar steps of staining and glazing. Both were done using the Ivocolor stains (Ivoclar Vivadent AG, Schaan, Liechtenstein) at a temperature of 710° C. This finalization takes place ideally in two steps so that the color adaptation and control of the result are implemented based on the colored 3D-models more efficiently, and exact control of the degree of gloss is possible (Figure 8). If the complete digital workflow is chosen, it is advisable to use a 3D-printed 3D-model to represent the scan data of the jaw so that both the fit and the proximal and occlusal contacts can be checked. For color control during staining and glazing, colored 3D-models show remarkable advantages, especially in providing the ideal way of adapting the staining of the restorations to the color of the model and thus to the situation in the patient's mouth (Figures 9–11).

FIGURE 4 3D-printed colored 3D-models (printed at 3D Medical Print KG, Lenzing, Austria)

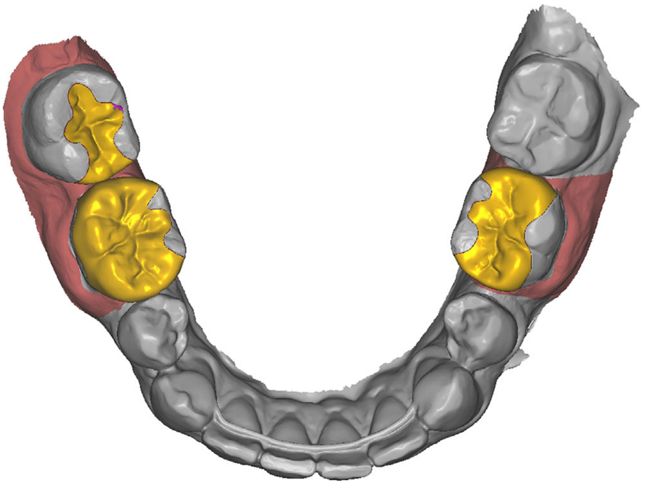

FIGURE 5 Exemplary CAD from the mandible restorations based on the data from the 3D-intraoral scanner using the Zirkonzahn Modellier software (version v.6173_6843_x64)

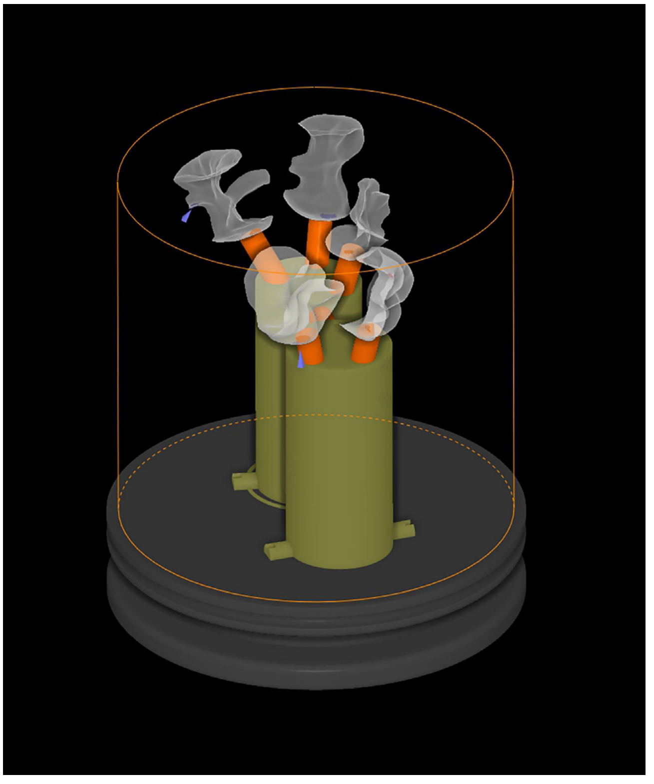

FIGURE 6 TrixCAD construction of the complete wax-up, including the placeholders for up to three pressing plungers

FIGURE 7 3D-printed components prepared for trixpress muffle (left); pressed restorations fixed at press sprue (right)

3 | DISCUSSION

Currently, there are numerous ways of manufacturing full ceramic restorations in dentistry and dental technology. Milestones for this variety were indeed the development and advancement of CAD-CAM technology, but the possibilities of 3D-printing also significantly expand the potential of the digital workflow.[12] A potential application of the concept is primarily based on capturing accurate intraoral data. IOS indicated the possibility of manufacturing fixed prostheses within the range of single crown restorations. In contrast, it is difficult to use IOS in fabricating cross-arch fixed prostheses.[1–5] Several factors, like scanning strategy, scanning software, illuminance, and color temperature, affect the trueness and precision of the resulting datasets.[3,4] Since IOS are an evolving device, further improvement in accuracy and precision are expected in the next years, as a workflow with IOS is considered to be as pleasant as well efficient for both patients and practitioners.[4]

The visual shade selection is subjective and influenced by operator-dependent factors,[10] so instrumental shade-matching systems seem to improve color matching in dentistry.[9] Methods, like spectrophotometers or IOS, were more reliable than visual methods tested for color shade matching.[6,7,9] However, color matching and transfer to a colored master model are in their initial stage, and no studies have dealt with color fidelity of IOS data related to colored 3D-models so far.

Currently, the calibration of IOS is performed extraorally by standardized procedures dependent on the system. Therefore, different light conditions in the oral cavity might lead to altered color measurement results, impacting a faulty color output regarding the printed colored 3D-models. The second influencing parameter is the production of multicolored 3D-models itself. One challenge is the correct color mix to achieve the exact tooth shade and the second challenge is to imitate natural opacity or transparency. Furthermore, critical appearance-associated parameters, such as surface texture, surface gloss, or fluorescence of tooth structure, are not yet implemented.

Whereas for monocolored 3D-models MJ and DLP technology are reported to be the most accurate and precise,[17,18] for colored 3D-models MJ seems to be the technology of choice.[19] Nevertheless, there is no comparative data between 3D printed color models and monochrome models at the moment.

The presented workflow should be critically analyzed regarding several parameters. In particular, the costs of colored 3D-models and

FIGURE 8 Finished partial crowns after staining and glaze firing

the total workflow cannot be precisely defined at present, as both model fabrication and data processing must currently be considered to be in a prototype phase. Due to the high investment costs for MJ-3D-printers, the prices for colored 3D-models will probably be higher than those of standard monochromatic 3D-models, which can be produced using lower-cost DLP- and SLA-3D-printers.

From the economic point of view, today, the application of a 3D-printed colored 3D-model still is improvident, especially for single restorations. When more restorations are fabricated, the application might be more reasonable to limit the risk a re-do of multiple restorations due to color misfit. The additional costs are distributed over several restoration units and, thus, reduced. It is essential to distinguish between time efficiency and cost efficiency. The material costs become significantly lower, by pressing ceramics, as three to five restorations (depending on the size) can be pressed with one press blank. When fabricated by milling, a complete lithium disilicate ceramic block of IPS e.max CAD is required for each restoration. The prices of the blanks are almost the same. This means that the ratio is 1:5 in favor of the press technology. All other process steps are the same in both workflows (fully digital and "Print and Press"-Technology). A further investigation would be meaningful to see how the material efficiency of the press technology compensates for the additional analog effort. It must also be taken into account that the hourly machine rates for CAM production are of particular importance. These rates include the acquisition costs and the variable costs of the grinders, abrasives, service, etc.

FIGURE 9 Exemplary individual stained mandibular restorations seated on the 3D-printed colored 3D-model

In contrast, the benefit for the dental technician seems to be even more valuable. On the one hand, the CAD design and automated sprueing of the restorations on the base former save time. On the other hand, the TrixPress process enables simultaneously pressing with several press plungers, saving time, investment material, and energy to heat the muffle. The main advantage of the multicolor 3D model is the possibility to simulate and three-dimensionally control the esthetic appearance of full ceramic restorations in the dental laboratory. This additional information can be particularly deployed in the case of heavily discolored teeth to control the masking ability of different materials (Figures 12–14), even more when translucent monolithic restorations are planned.

Conventional pressed lithium disilicate ceramics exhibit excellent long-term data in esthetics, design, biological properties, and patient's opinion. These reliable results can be expected in the described workflow since the pressing process and thus the properties of the material do not differ.[22,23] Alternatively to the described process, the designed restorations could directly be milled from one of the numerous monolithic CAD-CAM processable materials on the market.[21] For

FIGURE 10 Detailed view of the final ceramic restorations seated on the colored 3D-model

FIGURE 11 Seated ceramic restorations 34 months after inserting

FIGURE 12 Initial situation with heavily discolored stumps in the anterior maxillary, that is, an esthetic region

FIGURE 13 3D-printed colored 3D-model with discolored stumps

FIGURE 14 Final inserted anterior crowns based on heavily discolored stumps

some of these materials, some progress is underway to possible calculate the translucency as the most important parameter of the optical appearance in relation to the material thickness before the manufacturing process.[25]

The use of definitive 3D-printed restorations is also conceivable (e.g., Varseo SmileCrown^{plus} (BEGO) or LCM (Lithoz GmbH)). Multicolor 3D-printed materials could achieve an even better esthetic result but are not yet available for intraoral use. Especially against the background of a novel possibility to capture internal structures by near-infrared (NIR) transillumination, which is already implemented in some IOS for caries detection.[8] This means that internal tooth structures, such as the dentin and pulp, might also be considered as input data in manufacturing colored 3D-models or prosthodontic restorations. These thinkable applications represent an exciting approach to create biomimetic histo-anatomic restorations that reflect the multilayered three-dimensionality in addition to the complex mechanical and optical properties of natural teeth.[14]

In summary, the described approach represents an innovative workflow to manufacture individual high-end full-ceramic restorations. Nevertheless, it must be emphasized again that the findings are based on the subjective experiences of the authors, as evidence-based literature on this novel workflow is not yet available. An efficient process chain can be achieved through the digital designing process of the restoration and the particularly flexible application of this concept. Furthermore, the introduced process shows how easy the digital and conventional workflow can be synchronized, including a great advantage of transferring color information to the dental laboratory, and making this information physically available by a colored 3D-model.

Future studies could investigate the "Print and Press" restorations' analytical parameters, such as accuracy of fit and marginal seal compared to conventional analog workflow. In addition, an investigation of the deviation between the tooth shade and the restoration shade is practical (color difference [ΔE]). Unfortunately, a better representation of translucency is currently not possible with the models. The additional color information should only facilitate the finalization of the restoration. Generally, the digital techniques need to be further developed and specified in data acquisition, data transfer, and model fabrication to incorporate additional parameters so that colored 3D-models can realize their full potential.

4 | CONCLUSIONS

This report described a novel hybrid workflow that expedites and facilitates the fabrication of full-ceramic restorations. The combination of excellent clinical long-term data for pressed ceramic restorations and proven modern concepts, like intraoral scanning and additive manufacturing, in the dental field might promise predictability and efficiency. 3D-printed colored 3D-models represent a new innovative technique with many potential areas of application.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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