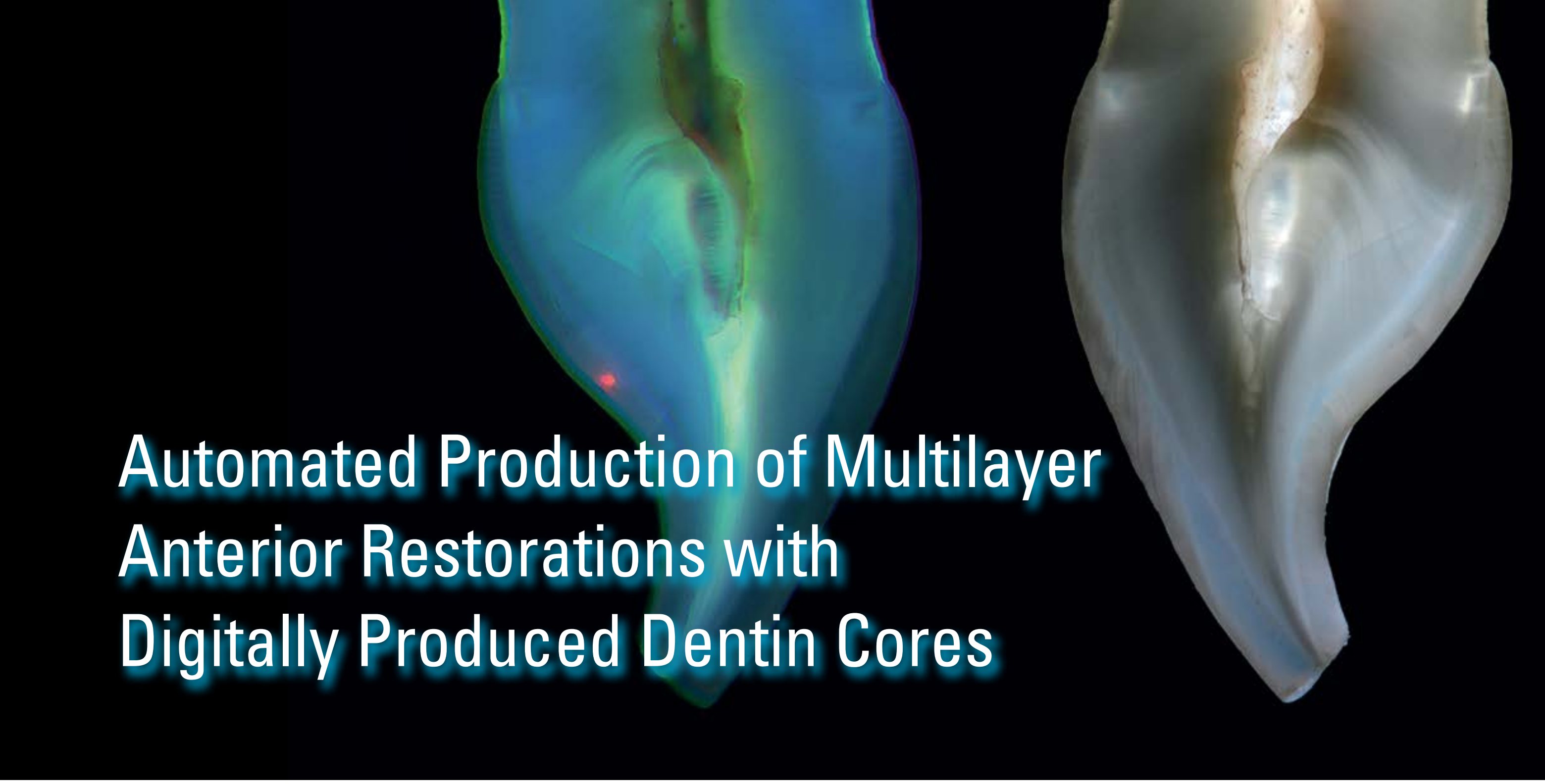

Automated Production of Multilayer Anterior Restorations with Digitally Produced Dentin Cores

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When producing digital dental restorations, it is now possible to mirror the geometry of teeth, to output the result as a data record, and to mill the resulting shape monolithically from a tooth-colored blank. The result is acceptable when restoring an entire anterior maxilla or mandible, although the esthetic results achieved with layered tooth build-ups will generally be more natural looking. The identical replication of adjacent teeth creates the illusion of "natural-identical" restorations.

Single maxillary anterior teeth, especially the central incisor, cannot be successfully realized as monolithic crowns, as these cannot adequately mimic the individually layered structure of anterior teeth. Here the craftsmanship of an experienced dental technician will continue to be required. But even the most skillful expert will have to redo maxillary anterior crowns at times, as the desired esthetic result does not always materialize on the first try.

In addition to the correct shape and surface, the shade also plays a significant role. In particular, the correct individual layering—or, in other words, the correct three-dimensional structure—of the crown is crucial for a perfect reproduction of a natural tooth.

The internal structure of the crown—especially the dentin—will determine the esthetics of an anterior restoration to a considerable extent. Experienced dental technicians are able to mimic the dentin in its three-dimensional manifestation but will generally not be

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able to provide any precise spatial definitions. The design of the dentin core is therefore based mainly on the training and the experience of the dental technician and often follows a "traditional" approach. Thus, almost all dental technicians leave a clearly discernible "signature" as they prepare their restorations, a restorative artefact that does not, strictly speaking, have any connection with the case at hand.

STATE OF THE ART

Ingots with Plane-Parallel Layers

Various approaches have been used to imitate the layered structure of natural teeth using digital methods. For example, various manufacturers offer ingots for computer-aided design/computer-assisted manufacture (CAD/CAM) processing that consist of several plane-parallel layers, with the individual layers having different shades. Examples include the Vitablocs TriLuxe forte ingot (Vita Zahnfabrik), the CEREC Bloc C PC (Sirona), and the Noritake Katana Zirconia ML disc (Kuraray Noritake). These ingots attempt to mimic the shade gradient of the natural tooth, from cementum and dentin to enamel, by presenting differently colored layers within the material. The software can modify the vertical alignment of the restoration within the ingot, allowing the chroma of the restoration to be modified. The esthetic results of restorations from these polychromatic blocks are certainly better than the esthetics of restorations made from monochromatic blanks. Nevertheless, they cannot be used to create customized, patient-specific layers.

Three-Dimensional Ingot Structure with Dentin Core and Enamel Coating

A second approach to imitating the layered structure of natural teeth is a millable ingot that has a three-dimensional block structure with dentin core and enamel coating and an arched gradient between the dentin and incisal (VITA RealLife Block, Sirona CEREC Blocs C In). The software can relocate the virtual design within the ingot such that the proportion of dentin and enamel is modified. This is supposed to give users the opportunity to imitate the appearance of natural teeth as closely as possible. But even these ingots cannot be used to produce customized, patient-specific layers.

Semi-finished Crowns

A third approach is that of the so-called semi-finished crowns, such as the priti crown (pritidenta), which already features the anatomical outer geometry of the clinical crown and a standardized layered structure of the dentin and incisal areas. The only thing left to do is use the CAD/CAM system to remove a volume corresponding to the prepared tooth in shape and form of the basal aspect of the crown. The disadvantage is that only subtractive processing is possible, so that slightly larger blanks are generally used that are reduced by milling to match the CAD design. Milling can never add material!

Tooth Databases

Systems for computer-aided manufacturing of dental restorations include tooth databases based on data from scanned natural teeth, scanned prefabricated teeth, or scanned manually waxed-up tooth shapes. However, these databases invariably refer only to the external tooth geometry.

Biogeneric Occlusal Surfaces

Sirona's CEREC system uses so-called "biogenic occlusal surfaces" (developed by Professor Dr Albert Mehl of the University of Zürich, Switzerland), which operates on the basis of several thousand scanned natural teeth. The system determines the closest match in the tooth database to the remaining tooth structure, "adds" the missing portions, and thereby obtains a very natural partial-crown (or inlay, or onlay) geometry. But even the "biogeneric tooth model" is confined exclusively to the external tooth geometry.[1] In the biogeneric tooth model, missing parts of the external tooth surface are added in by adapting a generic record of the desired tooth to the residual tooth structures and/or antagonists and/or adjacent teeth

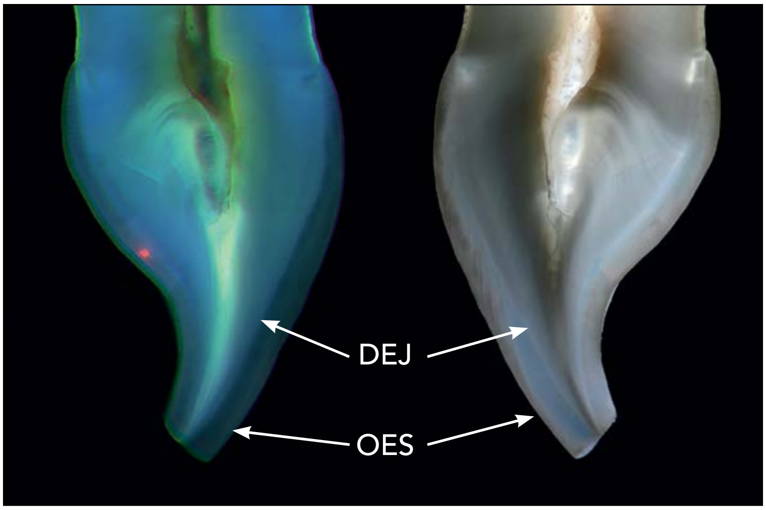


Fig 1 Sagittal sections of anterior crowns. The dentinoenamel junction (DEJ) and the outer enamel surface (OES) are clearly discernible.

situation and/or bite registration. Furthermore, Sirona provides a database for the CEREC system in which the user is presented with a static mamelon structure, generated according to geometric design guidelines, which is then customized by CAD and produced by CAM in the milling unit.

In his doctoral thesis, Probst[2] described the morphology of maxillary anterior teeth and the determination of similarity metrics of identical anterior tooth types in the left and right maxilla. However, he did not address the layered internal three-dimensional structure of anterior teeth.

Looking at the current state of the art as just presented, it can be summarized that no database is currently available for the layered internal three-dimensional tooth structures in the anterior and posterior regions. The term "tooth-structure database" as used below denotes a database/library that includes internal three-dimensional tooth structures and the corresponding surfaces of the respective specific teeth in digital and/or physical form. Neither has a method been described for the automated generation of the layered internal tooth structure, especially the dentin.

DEJ AND OES

By far the largest part of the human tooth consists of dentin, which forms the inner "protective coating" for the pulp cavity in its center. The pulp consists mainly of loosely packed connective tissue with numerous cells, intercellular basic substance, reticular and collagen fibers, and—not least—nerves and blood vessels.[3] The dentin in turn is covered by enamel in the clinical crown area and by cementum in the root area. Together, enamel, dentin, and cementum represent the hard tissue of the human tooth. The enamel is the hardest substance in the human body, with a Vickers hardness of 250 to 550 and a compressive strength of 300 to 450 MPa. Its modulus of elasticity is 50,000 to 85,000 MPa.[4] The dentin, by contrast, is much more elastic (Young's modulus of 15,000 to 20,000 MPa), because it contains a significantly higher percentage of organic matter. The Vickers hardness of the dentin is 60 to 70, and its compressive strength is 200 to 350 MPa.[4] The cementum is similar to human bone in both structure and hardness but differs from bone in that it is not vascularized. The cementum is already considered part of the attachment apparatus, or periodontium. This is where the periodontal fibers are attached that keep the teeth in their bony sockets, or alveoli.[3]

The dentinoenamel junction (DEJ) and the outer enamel surface (OES) (Fig 1) are essential features of the three-dimensional structure of the tooth and significantly affect its visual appearance. Some study results indicate that the DEJ provides considerable information about the OES.[5–25] It is known that the shape of the DEJ closely resembles the shape that the OES reflects[6,7,26] and that, unlike the OES, the DEJ is preserved intact in abraded teeth.

There are different ways to represent the DEJ in three dimensions, as described as follows.

Chemical Removal of the Enamel Layer

Chemical removal of the enamel layer is a destructive method for preparing the DEJ. The entire enamel layer can be removed with 37% phosphoric acid.[5,15–18] Since the enamel layer is destroyed in the process, it is necessary to preserve the OES. This can be done in an analog manner, by taking an impression of the tooth crown and subsequent pouring of a cast, or digitally, by scanning the tooth crown. The scan operation can be performed mechanically (eg, Procera Forte, Nobel Biocare) or by means of an optical scanner (eg, BEGO 3Shape D 700, Bego Medical).

Computed Tomography

The three-dimensional geometry of the OES and DEJ can be acquired by standard computed tomography (CT) or cone beam computed tomography (CBCT). The resolution and accuracy of the data vary greatly depending on the manufacturer. Therefore, it is often difficult to obtain 3D data sufficiently accurate for further processing from CT or CBCT data. The InVesalius software (CTI Renato Archer) can convert two-dimensional data from CT scans to three-dimensional DICOM (Digital Imaging and Communications in Medicine) data. These DICOM data are then converted to STL (Standard Tessellation Language) data.[27–29]

Microcomputed Tomography

The best way to acquire three-dimensional OES and DEJ data is by microcomputed tomography (microCT). In the study presented here, the extracted teeth were scanned with the exaCT S S60 HRE desktop CT unit (Wenzel Volumetrik). The voxel size was 45 μm. The exaCT Analysis software (Wenzel) was used for data acquisition and output. The data for the enamel (with the OES on the outside and the DEJ on the inside) and the root with dentin core (DEJ) and pulp chamber were converted to the STL format and output.

PRINCIPLE OF THE DENTIN-CORE CROWN

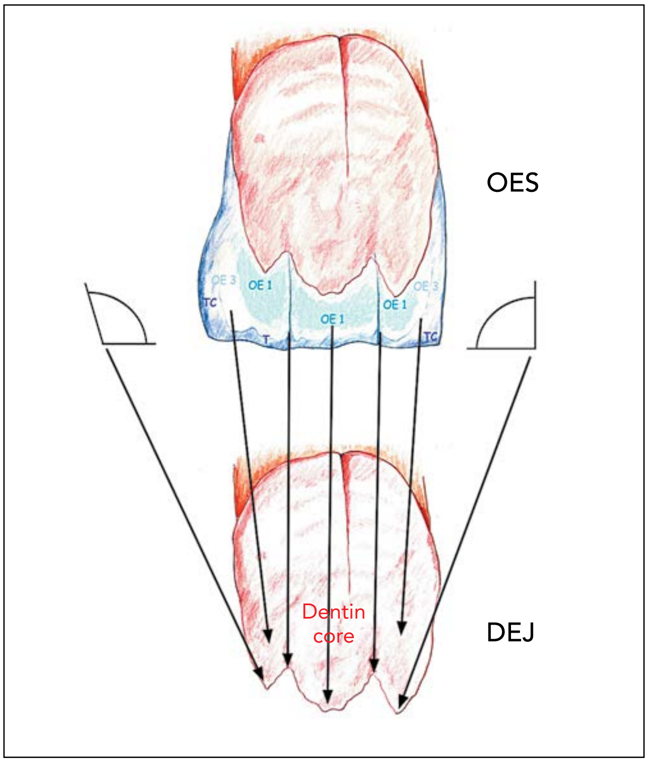
As early as 1945, Weidenreich had noted that the surface relief of the dentin (the DEJ) could not be a purely accidental feature without any morphologic importance.[19,30] The basic principle of the digital dentin-core crown/digital dentin-core bridge according to Schweiger[31] is as follows: "There is a clear correlation between the three-dimensional tooth surface (OES) and the layered internal structure of a tooth (the dentin core and DEJ)" (Fig 2). As used here, the term "correlation" signifies the association of a record describing the structure of the internal layer (ie, the DEJ) with a record defining the external geometry of the tooth (ie, the OES).

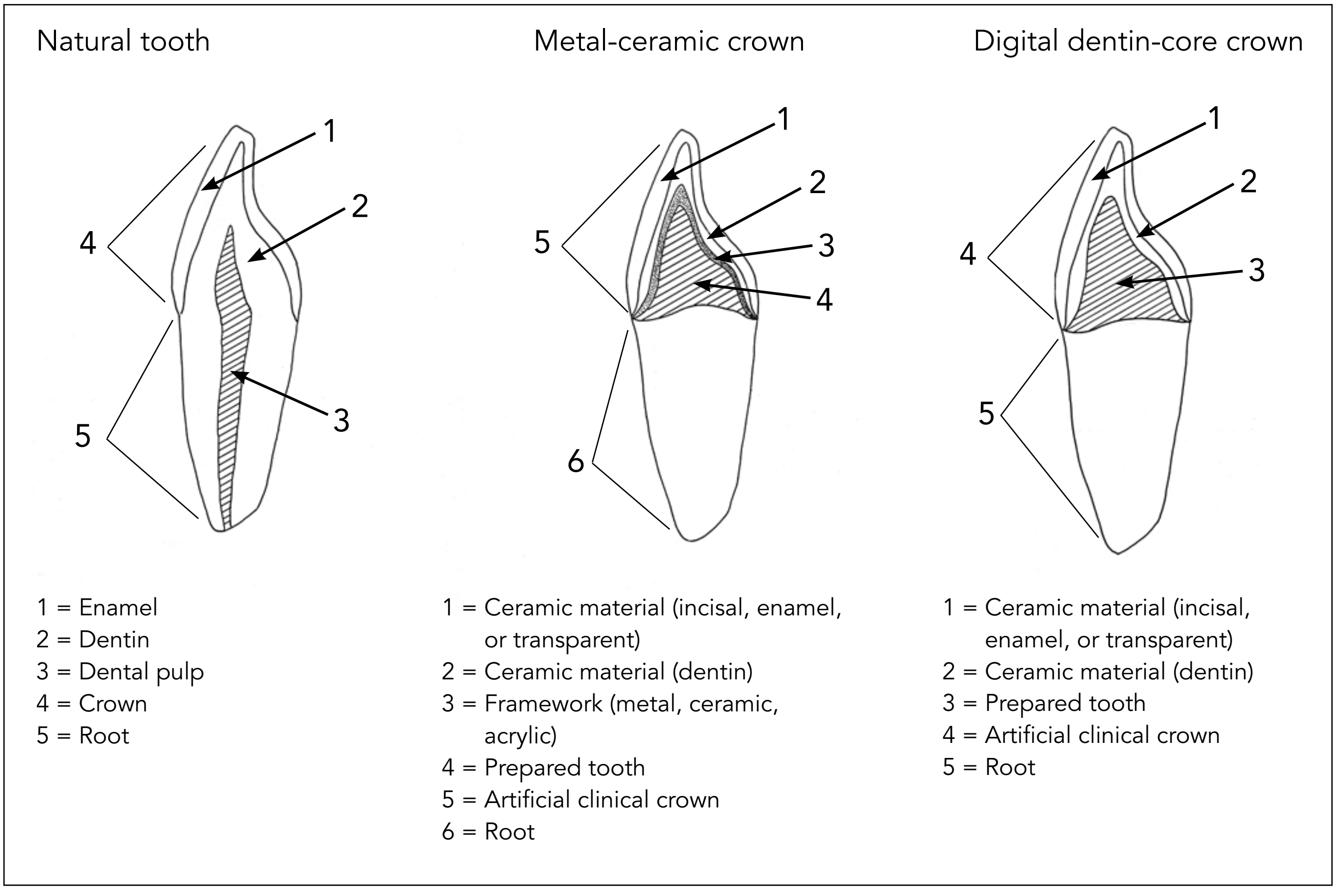
Based on this axiom,[32] a tooth-structure database can be compiled that allows, for the first time, crown or bridge restorations to be produced accurately and with an esthetic appearance that replicates the natural model (Fig 2).

Tooth-Structure Database

The idea on which the invention is based calls for acquiring not only the outer structures of the tooth but also the layered internal tooth geometry and to use it in conjunction with the external geometry, for example by storing them in a database (Figs 3 to 9).[31,33,34] If the external and layered internal tooth structures can be connected with each other dynamically, this is a particular advantage, as a virtual modification of the external geometry of the tooth can then be reflected by corresponding changes in the internal structure. Another advantage is that the digital acquisition of a large number of three-dimensional external and internal tooth geometries allows the establishment of a well-defined relationship between the layered structure of the inner tooth and its outer shape. Furthermore, once a suitable external geometry has been selected, the database can propose an internal tooth geometry that, with great probability, will correspond to the internal geometry of the natural tooth.

Fig 2 Principle of the digital dentin-core crown according to Schweiger (“inward biogenerics”). OES = outer enamel surface. DEJ = dentinoenamel junction.





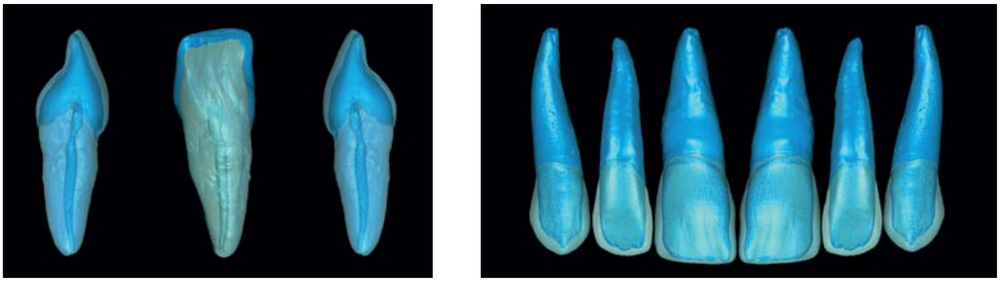
1 = Enamel
2 = Dentin
3 = Dental pulp
4 = Crown
5 = Root

1 = Ceramic material (incisal, enamel, or transparent)
2 = Ceramic material (dentin)
3 = Framework (metal, ceramic, acrylic)
4 = Prepared tooth
5 = Artificial clinical crown
6 = Root

1 = Ceramic material (incisal, enamel, or transparent)
2 = Ceramic material (dentin)
3 = Prepared tooth
4 = Artificial clinical crown
5 = Root

Fig 3 Natural tooth, metal-ceramic crown, and dentin-core crown (longitudinal sections).

Fig 4 Natural tooth with corresponding dentin core.



Figs 5a and 5b STL records from a tooth structure database of the outer enamel surface and the dentinoenamel junction.

Fig 6 CAD/CAM dentin cores, manufactured based on STL data of the dentinoenamel junction.

Fig 7 Virtual rendering of the outer enamel surface and the CAD/CAM dentin cores.

Correlations between the external and internal tooth geometries are recognized, for instance when certain types of tooth shapes (eg, oval, square, triangular) are associated with characteristic internal tooth structures (eg, pronounced mamelons in the case of projecting triangular teeth). Tooth types can be further subdivided into different shape groups by looking at tooth-specific surface and shape characteristics, including:

- Mesiodistal curvature
- Incisocervical curvature
- Rounding of the distal incisal edge
- Rounding of the mesial incisal edge
- Angle characteristics
- Incisal edge contours
- Surface-structure components such as longitudinal grooves or elevations

Data records of scans can be assigned to shape groups either by visual inspection or digitally using the best-fit alignment method. Either way, the result will be a database of teeth that subdivides the different tooth types into multiple shape groups.

Similarly, it is possible to assign the acquired internal tooth structures (especially the dentin cores) of the various tooth types (central incisors, lateral incisors, canines, first and second premolars, first to third molars) to different shape groups by using the same method. Here, again, the assignment can be made by visual inspection or using the best-fit alignment method. The result is a database of internal tooth structures, again subdivided into multiple shape groups. In addition, it is possible to establish a correlation between the internal and external tooth geometries. Using the database data, an internal tooth geometry is proposed for a given external tooth shape. It is highly probable that this proposal corresponds to the "real" internal tooth geometry (Figs 8 and 9)—the more so, the more records are included in the tooth database. BEGO Medical already realized this in its Dentaldesigner software from 3Shape. This software stored, for the first time, tooth geometries that are created on the basis of the real tooth.

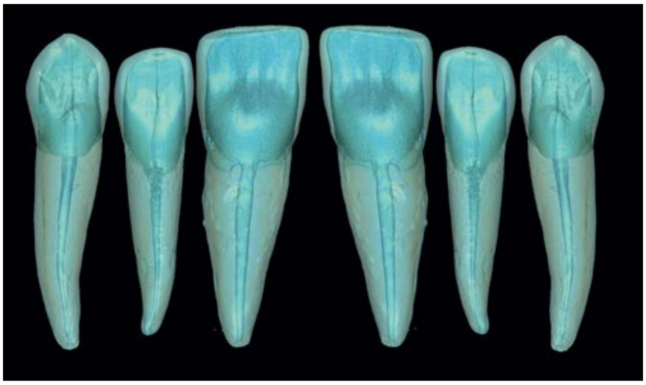
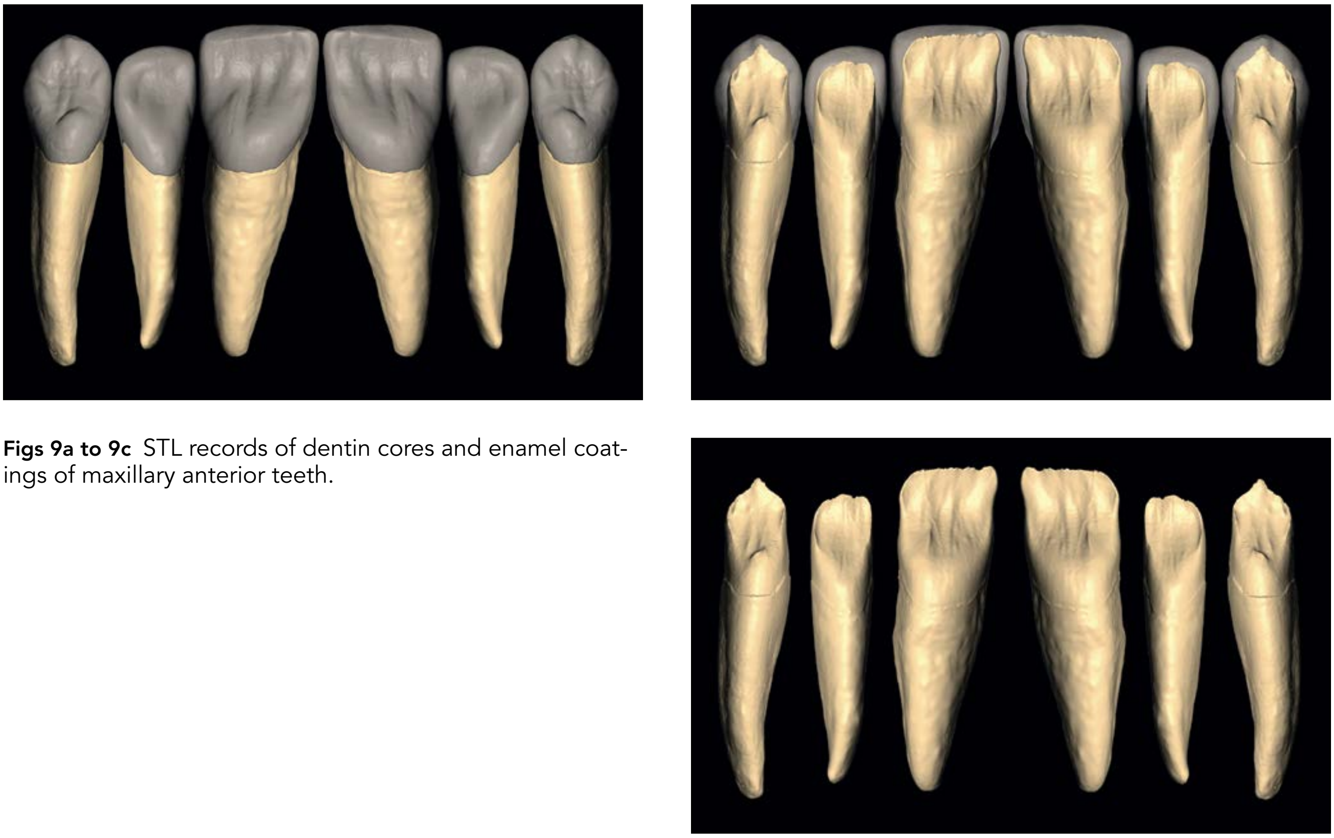


Fig 8 Palatal view of tooth structure data of maxillary anterior teeth, showing the dental pulp, the dentinoenamel junction, and the outer enamel surface.



Figs 9a to 9c STL records of dentin cores and enamel coatings of maxillary anterior teeth.

A novel application—the biogeneric tooth model—is also supported. This model calculates, based on the vast number of different tooth records in the database, an internal tooth geometry (eg, a dentin core) that has all the features characteristic of the respective tooth type. This is not achieved by merely averaging or superimposing the individual data points (x_n, y_n, z_n) that describe the internal tooth geometry, as this would result in noisy, unstructured data that do not correspond in any way to the typical geometry. Rather, the dentin core is segmented into individual building blocks (mamelons, incisal grooves, incisal contours of the dentin, etc) to uncover correspondences and to compare like with like. This prevents essential structures of the dentin core from being averaged out in calculating the geometry, as happens, for example, with mamelons during conventional alignment calculations, for example with regard to mamelons. This method produces an average internal tooth geometry with averaged values for the characteristic building blocks, such as mamelons, incisal grooves, incisal edges, etc.

In the next step, the deviation of the individual internal geometries from the respective average geometry is calculated by a principal-axis transformation. If the goal is to reconstruct a layered internal tooth structure, the biogeneric tooth model must be correlated with the external tooth geometry. Here, the layered internal tooth structure—especially the dentin core—corresponds to the missing hard tissue of the tooth substance in a biogeneric inlay reconstruction. A certain spatial distribution of a few design points on the external tooth surface requires a certain morphology of the dentin core. The combination of an average dentin core with the biogeneric model of the external tooth geometry makes it possible to assign the most probable dentin core to a given external tooth geometry. The morphologic relationship between the external tooth geometry and the layered internal tooth structure is essentially based on a genetic blueprint. The probability is high that a specific external tooth geometry can be correlated with a specific layered internal tooth structure, especially with regard to the dentin core, and vice versa. It should be pointed out in this context that one of the lead structures during odontogenesis is the preformative membrane, which eventually forms the DEJ.

This membrane is an anatomical structure that forms during tooth development. As a basement membrane, it constitutes the interface between the mesenchymal connective tissue (the mesodermal papilla) and the ectodermal enamel organ. Shortly before the dentin begins to form, this basement membrane thickens and henceforth separates the dentin from the enamel. Here, odontoblasts and ameloblasts are initially located back-to-back as the pre-dentin/pre-enamel is converted, gradually moving away from each other while the hard tissues of the tooth they have formed are left behind.

Once the external tooth geometry has been digitally linked to the internal tooth geometry, a correlation is formed between the two records, a correlation that can be either dynamic or static. In a static correlation, the internal geometry is not changed by a modification of the outer geometry, which among other things implies that the dentin core always retains its shape. In a dynamic correlation, however, the internal tooth structure is modified in response to any modifications of the external tooth surface. On modifying the external tooth geometry, all X/Y/Z values of the internal tooth geometry change proportionately to the X/Y/Z values of the external tooth geometry (scaling). Rotations will be performed with the same angle, and translations with the same X/Y/Z values will be performed by adding the translation values.

This database with correlations between the internal and external tooth geometries (correlations database) can be used in different ways in the production of dental restorations. Using computer-assisted output devices (computer numerical control [CNC]; rapid prototyping [RP]), restorations can be produced that mimic the layered internal structure of a natural tooth. The internal structure of the restoration is produced based on a record from the database, where the external surface corresponds exactly to the internal tooth structure of a record selected from the database. Suitable materials for creating the internal core include materials with a toothlike esthetic appearance in terms of shade and translucency, especially resin, glass ceramics, feldspar ceramics, lithium disilicate ceramics, and oxidic high-performance ceramics such as zirconia and alumina. Once this computer-generated internal aspect of the restoration has been produced, the incisal aspects can be added. This can be performed manually using a ceramic layering technique or a wax-up technique with subsequent overpressing. Alternatively, this incisal area can be designed by subtracting the internal tooth structure from the external tooth surface, creating a differential record that can be transformed into a real-world object using a CAM procedure. In a subsequent additive step, this incisal area is then connected to the dentin core by sintering (using a ceramic connector mass), by a polymerization process, or adhesively.

In the context of the method described here, there are several ways to design and manufacture dental restorations digitally (Fig 10), as shown below.

Best-fit alignment

The arch situation comprising the teeth to be replaced as well as the adjacent teeth is acquired by three-dimensional scanning (intraoral or extraoral). If a "mirror tooth" is present, its three-dimensional structure is mirrored. A study[2] has shown that mirror-image replacements of anterior teeth are satisfactory with respect to interproximal, occlusal, and esthetic aspects. Using an iterative procedure, the external structure of the mirror-image tooth is compared to and correlated

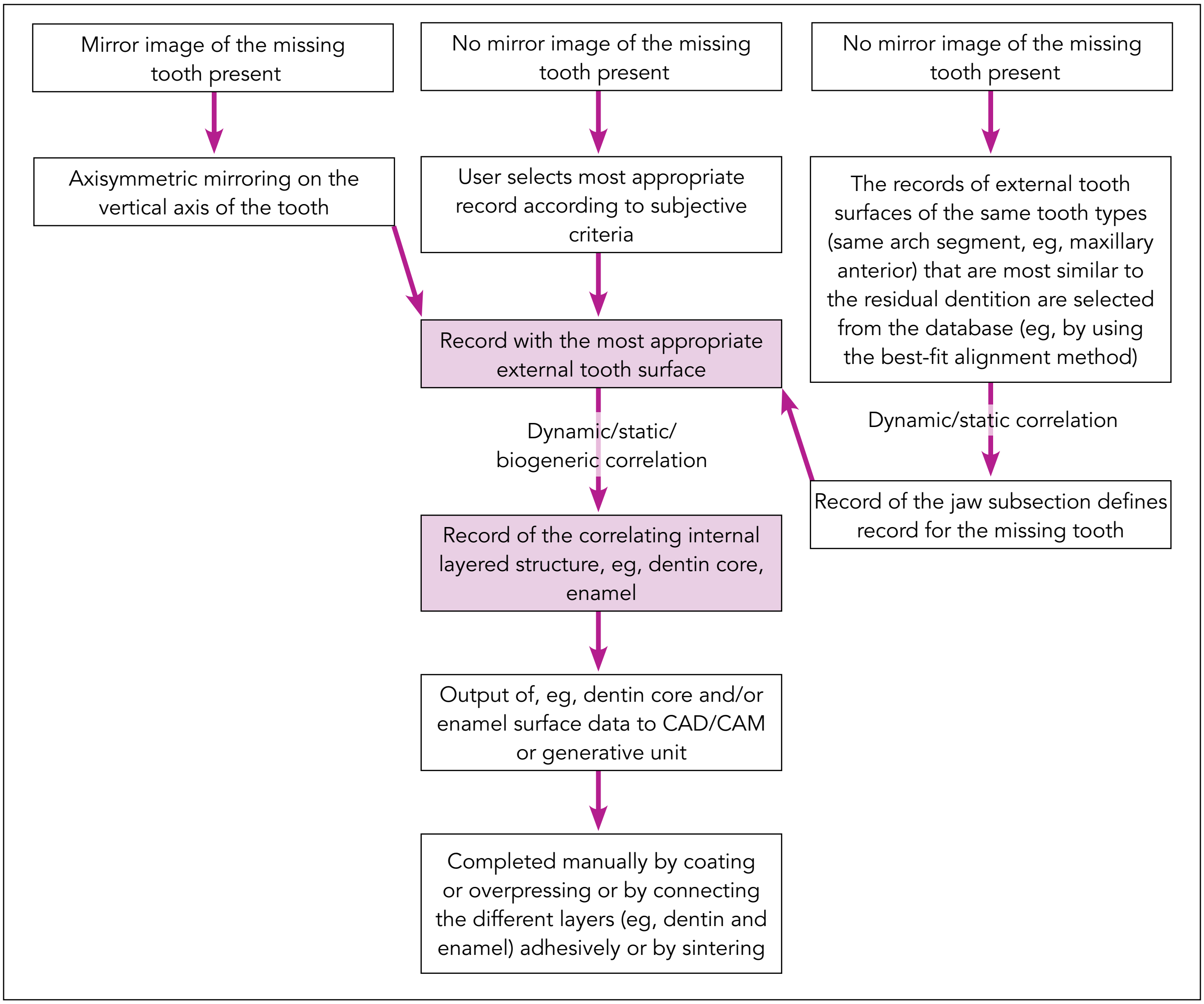


Fig 10 Schematic representation of the fabrication of dental restorations with the aid of a tooth-structure database.

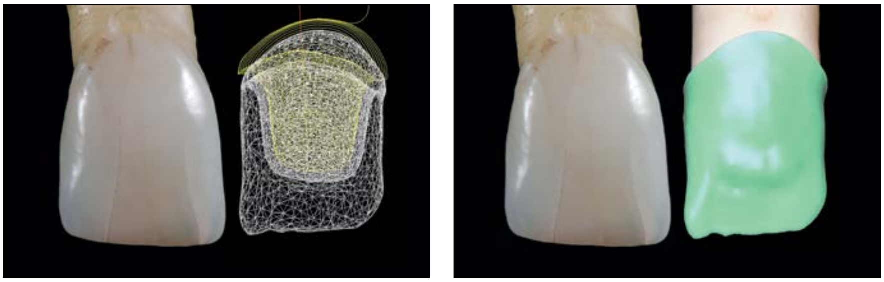
with the natural or manually designed teeth in the correlations database until the most appropriate record is found. To determine the appropriate record by way of an iterative procedure, it is possible to devise a similarity metric based on the standard deviation of the smallest distances of points on the surface of the mirrored tooth from the respective closest points of each tooth record in the database.

$$SD = \sqrt{\frac{\sum_{i,j}^{n}[(X_{1i}-x_{2j}) + (y_{1i}-y_{2j}) + (z_{1i}-z_{2j})]^2}{n}}$$

(SD = standard deviation over the shortest distance = similarity metric)

This method is also called "best-fit alignment." To achieve a best-fit alignment, the tooth is mirrored and then superimposed on a reference tooth from the database in the optimal position by rotation, translation, and possibly also scaling. Image analysis software (eg, Geomagic Qualify, Geomagic GmbH) can be used for this. As a layered internal tooth structure exists for the best-fitting record, this structure can be used for designing the restoration, and specifically its dentin core, using computer-assisted methods. Once the dentin core has been created, the incisal aspect can be built up manually; alternatively, a CAM-created incisal segment can be connected to the dentin core by sintering or adhesively.

Fig 11 Maxillary right central incisor and the corresponding die of the left central to be restored.



Figs 12a and 12b STL data of the mirrored dentinoenamel junction of the maxillary right central.

Customizing the data according to user preferences

The arch situation comprising the teeth to be replaced as well as the adjacent teeth is acquired by three-dimensional scanning (intraoral or extraoral). If no mirror-image tooth is present, a record presumed to be appropriate is selected from the database and can be three-dimensionally adapted to the actual situation by rotation, translation, and scaling. Due to the dynamic correlation of the record of the three-dimensional external tooth geometry with the record of the three-dimensional layered internal tooth structure, a design for a layered core, eg, a dentin core, will be suggested. The suggested dentin core can then be customized as required. The three-dimensional record is implemented physically on a computer-assisted output device such as a CNC or RP unit.

Best-fit alignment after customizing the data according to user preferences

The arch situation comprising the teeth to be replaced as well as the adjacent teeth is acquired by three-dimensional scanning (intraoral or extraoral). If no mirror-image tooth is present, the software compares the residual dentition with the records from the database of arch segments, and the record presumed to be the most appropriate is selected using the best-fit alignment method. Since this record is assigned to exactly one record of the missing tooth, it can serve as a basis for the tooth to be replaced. Due to the dynamic correlation of the three-dimensional external tooth geometry with the three-dimensional layered internal tooth structure, a design for a layered core, eg, a dentin core, will be suggested. The suggested dentin core can then be customized as required. The three-dimensional record is implemented physically on a computer-assisted output device such as a CNC or RP unit (eg, Bego Medical).

Automated Manufacturing Process for Individual Anterior Crowns

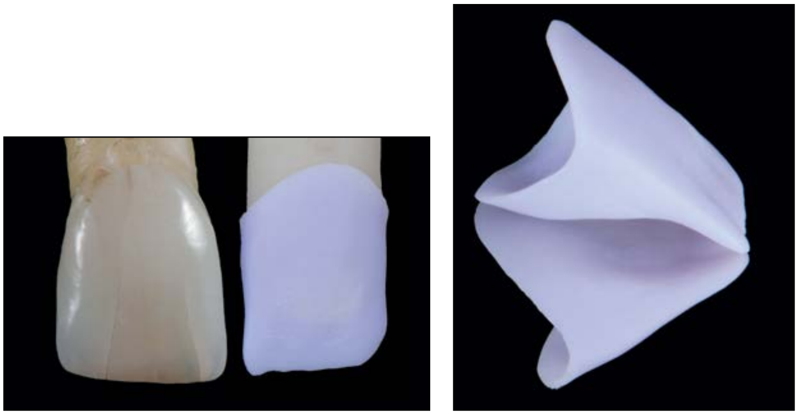
Using tooth-structure databases it is possible to produce—using a partially or fully automated process—highly esthetic restorations, especially for the anterior region.

Let us assume a single anterior crown is to be provided for the maxillary left central incisor using a digital process, where the natural right central incisor is used as a template. Producing a single crown for a maxillary central incisor is considered one of the most difficult challenges in prosthodontics. The procedure consists of the following steps:

1. Acquiring the external tooth surface
2. Identifying the matching dentin core
3. Mirroring the external tooth surface and dentin core data
4. Digital manufacturing of the dentin core
5. Adding the incisal region
6. Digital finishing of the tooth surface
7. Finalizing the crown (glaze firing, polishing, etc)

Acquiring the external tooth surface

The external surface of the natural right central incisor can be acquired by three-dimensional digital scanning (Fig 11) with a mechanical or optical scanner or using a sonographic or radiologic procedure such as CT, CBCT, or micro-CT.



Figs 13a and 13b CNC-milled dentin core made of lithium metasilicate to restore the maxillary left central.

Fig 14 Dentin core from lithium disilicate after crystallization at 840°C.

Identifying the matching dentin core

The dentin core matching the external surface of the tooth dentin can be determined based on the tooth structure database. The acquired surface data are compared with the records of tooth surfaces in the tooth-structure database, and the record that is in closest agreement with the newly acquired data is selected. In the tooth-structure database, each external tooth surface is associated with a unique dentin core. Consequently, it is possible, on the basis of the acquired data, to identify the matching dentin core.

Mirroring the external tooth surface and dentin core data

Next, the two records are mirrored (Fig 12) to produce the crown based on the mirrored external tooth surface and dentin core data.

Digital manufacturing of the dentin core

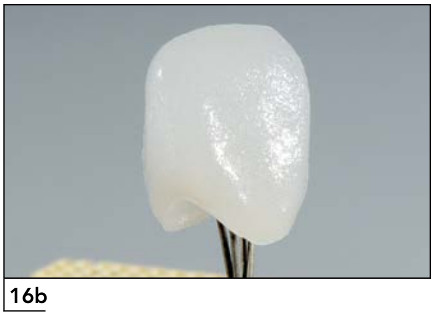
Using dental CAD software, the record of the digital dentin core can be placed on the prepared tooth. The three-dimensional orientation of the dentin core data set is determined by the external tooth surface data. Next, the CAM software calculates the milling paths and corresponding NC file based on the CAD record of the dentin core. In the example shown, the dentin core was produced using the Everest unit (KaVo) and was prepared using the "counter-bed" procedure. In this procedure, once the cavity side has been milled, the cavity is filled with polyurethane resin. Once the resin has hardened, the surface of the dentin core (the DEJ) is milled. The material used was lithium disilicate (IPS e.max CAD LT, Ivoclar Vivadent). A side benefit of the counter-bed procedure is that it produces a copy of the die in polyurethane that is precisely positioned within the CNC unit in relation to the machine zero and workpiece zero points, facilitating precise repositioning of the crown within the CNC unit. The CAM process uses diamond grinding points. The IPS e.max CAD material is present in the metasilicate phase because it is easier to mill in this phase. After milling, the dentin core is crystallized at 840°C; then the lithium metasilicate is converted into lithium disilicate, attaining the target tooth shade and the final strength of 360 MPa (Figs 13 and 14).

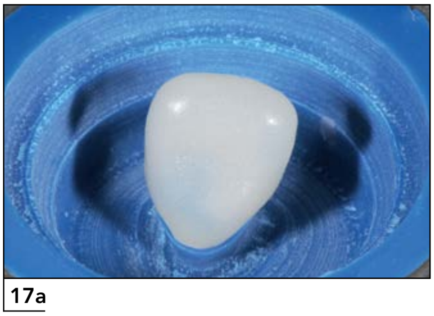
Adding the incisal region

The ceramic veneer was made of IPS e.max Ceram (Ivoclar Vivadent). Before the actual application of the ceramic in the incisal area, a wash firing was performed at 760°C. Experience has shown that a mixture of Transpa Incisal and Opal Effect 1 at a ratio of 1:1 achieves a good result when using the incisal single-layer technique. Material is applied generously to the incisal area to provide enough bulk for the subsequent subtractive process. Once applied, the ceramic material is fired at 750°C (Figs 15 and 16).


15


16a


16b


17a


17b


17c


17d


18

Fig 15 Application of incisal veneering material (IPS e.max Ceram, 50% Transpa Incisal 2, 50% Opal Effect 1).

Figs 16a and 16b The ceramic material is fired at 750°C.

Figs 17a to 17d The tooth surface is machined based on the three-dimensional record of the outer enamel surface. Repositioning is done with the aid of the polyurethane "copy."

Fig 18 The restoration is completed with a stain and glaze firing.

Digital finishing of the tooth surface

After ceramic firing, the entire crown is repositioned on the polyurethane die that was produced by the counter-bed process. Next, the tooth surface is machined based on the three-dimensional record of the outer enamel surface (Fig 17). The result is a two-layer restoration in which both the inner dentin core and the outer enamel surface were obtained in a digital procedure.

Finalizing the crown (glaze firing, polishing, etc)

The manufacturing process is finalized with a stain-and-glaze firing and final polishing of the restoration (Fig 18).

Fig 19 *(Left to right)* Natural tooth, CAD/CAM-fabricated anterior crown on tooth, 3D-printed (RP) tooth.

CONCLUSIONS

The process described in this article allows, for the first time, fabrication of highly esthetic anterior restorations based on tooth structure records in a digital, and therefore reproducible, procedure. The result is predictable, and good outcomes can be achieved even by users who are experienced in these technical matters. The digital dentin core is the key to digital anterior esthetics. It is important to create tooth structure databases that contain data both for the external geometry of the teeth and the corresponding dentin cores. The data for natural teeth especially will open up an entire new dimension of natural anterior esthetics. Production options include both subtractive and additive manufacturing processes (Fig 19).

Users have the ability to access a wide variety of tooth shapes and their structural designs to achieve reproducible results. Ultimately, it should be possible to use the digitally acquired external geometry of a tooth to identify the corresponding dentin core from a database in a highly predictable manner. Future research projects will have to demonstrate the statistical relationship between the external tooth shapes and dentin cores.

REFERENCES

1. Mehl A. Verfahren zur Herstellung von Zahnersatzteilen oder Zahnrestaurationen unter Verwendung elektronischer Zahndarstellungen. German patent no. 102 52 298 B3, 2002.
2. Probst F. Dreidimensionale Untersuchungen zur Morphologie der oberen Frontzähne [thesis]. Munich: Ludwig-Maximilians University, 2009.
3. Hellwig E, Klimek J, Attin T. Einführung in die Zahnerhaltung, ed 2. Munich-Jena: Urban & Fischer, 1999: 3–11.
4. Körber K. Funktionslehre. In: Zahnärztliche Prothetik. Stuttgart: Georg Thieme, 1995:3–7.
5. Kraus BS. Morphologic relationships between enamel and dentin surfaces of lower first molar teeth. J Dent Res 1952;31:248–256.
6. Korenhof CAW. Morphogenetical Aspects of the Human Upper Molar. Utrecht, The Netherlands: Uitgeversmaatschappij, 1960.
7. Korenhof CAW. The enamel-dentine border: A new morphological factor in the study of the (human) molar pattern. Proc Koninkl Nederl Acad Wetensch 1961;64B:639–664.
8. Korenhof CAW. De evolutie van het ondermolaarpatroon en overblijfselen van het trigonid bij de mens (I). Ned Tijdschr Tandheelkd 1978;85:456–495.
9. Korenhof CAW. Evolutionary trends of the inner enamel anatomy of deciduous molars from Sangiran (Java, Indonesia). In: Kurtén B (ed). Teeth: Form, Function and Evolution. New York: Columbia University Press, 1982:350–365.
10. Nager G. Der Vergleich zwischen dem räumlichen Verhalten des Dentinkronenreliefs und dem Schmelzrelief der Zahnkrone. Acta Anat 1960;42:226–250.

11. Schwartz GT, Thackeray JF, Reid C, van Reenan JF. Enamel thickness and the topography of the enamel-dentine junction in South African Plio-Pleistocene hominids with special reference to the Carabelli trait. J Hum Evol 1998;35:523–542.
12. Sakai T, Hanamura H. A morphology study of enamel-dentin border on the Japanese dentition. Part V. Maxillary molar. J Anthropol Soc Nippon 1971;79:297–322.
13. Sakai T, Hanamura H. A morphology study of enamel-dentin border on the Japanese dentition. Part VI. Mandibular molar. J Anthropol Soc Nippon 1973a;81:25–45.
14. Sakai T, Hanamura H. A morphology study of enamel-dentin border on the Japanese dentition. Part VII. General conclusion. J Anthropol Soc Nippon 1973b;81:87–102.
15. Sakai T, Sasaki I, Hanamura H. A morphology study of enamel-dentin border on the Japanese dentition. Part I. Maxillary median incisor. J Anthropol Soc Nippon 1965;73:91–109.
16. Sakai T, Sasaki I, Hanamura H. A morphology study of enamel-dentin border on the Japanese dentition. Part II. Maxillary canine. J Anthropol Soc Nippon 1967a;75:155–172.
17. Sakai T, Sasaki I, Hanamura H. A morphology study of enamel-dentin border on the Japanese dentition. Part III. Maxillary premolar. J Anthropol Soc Nippon 1967b;75:207–223.
18. Sakai T, Sasaki I, Hanamura H. A morphology study of enamel-dentin border on the Japanese dentition. Part IV. Mandibular premolar. J Anthropol Soc Nippon 1969;77:71–98.
19. Skinner M. Enamel-dentine junction morphology of extant hominoid and fossil hominin lower molars. J Hum Evol 2008;54: 173–186.
20. Corruccini RS. The dentinoenamel junction in primates. Int J Primatol 1987;8:99–114.
21. Corruccini RS. Relative growth from the dentino-enamel junction in primate maxillary molars. J Hum Evol 1987;2:263–269.
22. Corruccini RS. The dentino-enamel junction in primate mandibular molars. In: Lukacs JR (ed). Human Dental Development, Morphology, and Pathology: A Tribute to Albert A. Dahlberg. Portland: University of Oregon Anthropological Papers, 1998: 1–16.
23. Corruccini RS, Holt BM. The dentinoenamel junction and the hypocone in primates. Hum Evol 1989;4:253–262.
24. Sasaki K, Kanazawa E. Morphological traits on the dentino-enamel junction of lower deciduous molar series. In: Mayhall JT, Heikkinen T (eds), Proceedings of the 11th International Symposium on Dental Morphology, Oulu, Finland, 1998. Oulu, Finland: Oulu University Press, 1999:167–178.
25. Gallagher RR, Demos SG, Balooch M, Marshall GW Jr, Marshall SJ. Optical spectroscopy and imaging of the dentin-enamel junction in human third molars. J Biomed Mater Res A 2003;64:372–377.
26. Butler PM. The ontogeny of molar pattern. Biological Reviews 1956;31:30–70.
27. Conroy GC. Enamel thickness in South African australopithecines: Noninvasive evaluation by computed tomography. Palaeont Afr 1991;28:53–58.
28. Conroy GC, Lichtman JW, Martin LB. Brief communication: Some observations on enamel thickness and enamel prism packing in the Miocene hominoid Otavipithecus namibiensis. Am J Phys Anthropol 1995;98:595–600.
29. Grine FE. Computed tomography and the measurement of enamel thickness in extant hominoids: Implications for its palaeontological application. Palaeont Afr 1991;28:61–69.
30. Weidenreich F. Giant early man from Java and South China. Anthropol Pap Am Mus Nat Hist 1945;40:1–134.
31. Schweiger J. Verfahren, Vorrichtung und Computerprogramm zur Herstellung eines Zahnersatzes. German patent, DE 10 2010 002 484 A1 (2010).
32. Hilbert D, Ackermann W. Grundzüge der theoretischen Logik. Berlin, Göttingen, Heidelberg: Springer, 1972:24.
33. Schweiger J. Method, Device and Computer Program for Producing a Dental Prosthesis. European patent, EP 000002363094 A2 (2011).
34. Schweiger J. Method, Apparatus and Computer Program for Producing a Dental Prosthesis. US patent 8, 775, 131, B2 (2011).