Chapter 39

THE USE AND IMPROVEMENT OF TECHNOLOGIES FOR MANUFACTURING METAL-FREE DENTAL CONSTRUCTIONS AS A COMPONENT OF HEALTH-PRESERVING ASPECTS OF SUSTAINABLE DEVELOPMENT

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DOI https://doi.org/10.30525/978-9934-26-539-6-39

INTRODUCTION

The growing attention of people to their health and appearance, fueled by publications in mass media and social networks, has significantly increased the aesthetic demands of patients[1]. Today, patients want restorations that are not only functional but also beautiful and aesthetically pleasing, indistinguishable from natural teeth. This has led to the significant development of cosmetic dental procedures and increased requirements for the aesthetic outcomes of therapy[2].

In the past, achieving an attractive appearance of teeth often required invasive and costly interventions related to the creation of fixed prosthodontic constructions[3]. Advancements in dental materials, their application technologies, and the introduction of adhesive techniques have expanded the possibilities for dentists and dental technicians[4]. These advancements have also made aesthetic dentistry more accessible to a broader range of patients. Moreover, such treatment has become less invasive and relatively straightforward[5].

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[1] Carlos E.F., Laercio W.V. Metal-free esthetic restorations (2-th edition). Quintessence, 2003.

[2] Terry, Douglas A., Geller, Willi. Esthetics and Restorative Dentistry (2nd edition). Quintessence, 2013.

[3] John M. Powers, John C. Wataha, Dental Materials. Foundations and applications, Elsevier, 2017.

[4] Pascal Magne, Urs Belser. Biomimetic restorative dentistry, Vol.1. Quintessence, 2022.

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This shift in perspective has resulted in patients increasingly seeking dental care solely for cosmetic purposes, aiming to improve the appearance of their teeth electively[6].

Metal-free constructions are the most optimal type of prosthodontics in these cases and many others involving fixed constructions[7]. They offer numerous advantages over other materials, including high aesthetics, good mechanical strength, chemical stability, biological inertness, and low thermal conductivity[8].

Achieving positive long-term outcomes is impossible without understanding the interaction of various influencing factors, such as knowledge and comprehension of clinical and laboratory manufacturing protocols, materials science, and the integration of digital protocols into the workflow[9].

1. Modern perspectives on the manufacturing process of metal-free constructions

To better understand the manufacturing process of metal-free constructions, it can be divided into several stages:

◆ Diagnosis (photo documentation, color determination, creation of diagnostic models, CT scan);

◆ Planning the future work (Wax Up, digital forecast);

◆ Tooth preparation for the chosen construction;

◆ Taking impressions according to the selected manufacturing protocol (analog, digital-analog, digital);

◆ Laboratory manufacturing of the metal-free construction (with the availability of additional equipment and specific skills, it is possible to create both temporary and permanent restorations directly in the clinic, without involving a laboratory);

◆ Fixation.

A critical prerequisite for the success of restorative treatment, alongside the precise implementation of the clinical and laboratory stages, is a correctly performed diagnosis.

In aesthetic dentistry, one of the key diagnostic and communication tools is the art and practice of obtaining static images, or photography, which serves as an effective means of information exchange between the dentist

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[6] Radi M., Carl F. Driscoll, Clinical Applications of Digital Dental Technology. John Wiley & Sons, Inc., 2023.

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and dental technician. Modern digital photography capabilities allow for instant image acquisition and distortion-free transmission to any recipient via email or other media.

Frederick Barnard once accurately expressed the importance of photography: "One picture is worth a thousand words."

Digital photography greatly facilitates data exchange and patient education. Clinical images allow for thorough analysis of the appearance of a smile and dental arches, verification of diagnostic wax modeling and provisional restorations, as well as evaluation of lip contours and other aesthetic parameters.

Standardized projection photographs simplify aesthetic analysis, including the evaluation of enamel distribution, optical effects, and tooth contours, identification of hypoplasia areas, and transparency of incisal edges.

In dentistry, intraoral targeted, general, and external photographic protocols are used. It is essential to remember that photographic equipment characteristics can significantly impact image quality, potentially rendering the photo unsuitable for clinical purposes. However, with proper application, optical characteristics can be analyzed in detail. Photos of prepared teeth with corresponding shade guides provide valuable information to the dental technician.

Color determination is a fundamental requirement for achieving a high aesthetic result. Despite the fact that color determination in dentistry is divided into two stages – visual (subjective) and instrumental (objective) – it is more of an art than a science, as the human eye remains the final authority. Optimal results are achieved by combining traditional artistic and scientific colorimetric methods.

Proper lighting conditions are a crucial requirement for accurate color determination. Operators (dentists, dental technicians, and assistants) are advised to identify colors under three lighting conditions: natural light, artificial light, and twilight. Specific shade and intensity variations can be detected using devices such as Full Spectrum, Demetron Shade Light, Kerr/Sybron, Lumin Shade Light, and Vident (Fig. 1).

Fig. 1

When conducting clinical trials of restorations, clinicians should use the same lighting conditions as the dental technician during their fabrication.

Fig. 2

The **objective method** of color determination involves the use of digital technologies and computer image analysis. Modern equipment and software allow for the detection of minute color variations in different areas of a tooth and the selection of the optimal combination of restorative materials to create the most aesthetically pleasing restoration. One such system is ShadeScan (Fig. 2), which analyzes a tooth's image and objectively reflects its color characteristics and transparency.

Like the human eye converts visible spectrum light waves into color perception, devices digitally process and analyze the same light waves optically. The program then compares the digital image with a database of color samples of restorative materials from a selected manufacturer, such as Vitapan 3-D Master and Classical; Vita, Chromascop (Ivoclar Vivadent), Shofu Vintage Halo (Noritake), Esthet X, and Dentsply/Caulk.

It is worth noting that despite the high correlation between digital image and software recommendations regarding the choice of materials for restoration fabrication, computer systems do not replace the knowledge, skills, and experience of dentists and dental technicians.

2. Diagnostic modeling

Diagnostic modeling is an integral part of therapy planning, allowing all participants (patient, dentist, and dental technician) to visualize and analyze the functional and aesthetic parameters of the anticipated changes even before performing restorative or surgical procedures.

Despite the significant time investment required for this stage, this diagnostic approach ensures a desirable outcome and helps identify potential challenges early on. Furthermore, diagnostic modeling eliminates misunderstandings among participants, facilitates communication, and minimizes the patient's chair time.

The diagnostic model serves as a primary diagnostic and communication tool, offering a true three-dimensional representation of either the initial state or the predicted changes. Such models include:

- **Initial state models**: These allow the dental technician to understand the patient's existing functional features and potential for modifications. Unfortunately, the diagnostic value of these models is often underestimated, despite their ability to provide insights into surface contours, textures, existing restorations, and adjacent teeth. These factors can significantly impact the color of the final prosthesis.

- **Diagnostic wax models**: These provide an overview of the process and ensure the feasibility of achieving the desired outcome. When planning treatment, the patient's facial features, lip position, speech, and personal preferences should be considered. Detailed diagrams, sketches, and comments simplify wax modeling to simulate the final restorative outcome. Patients analyzing diagnostic wax models can offer feedback for adjustments (Fig. 3). Approved diagnostic wax models are then used to create templates for correction of various parameters, as well as guides for tooth preparation volume.
- **Provisional restoration models**: These are essential for planning surgical interventions on soft tissues or bones, determining necessary augmentation or resection, and selecting the optimal placement for implants. They are also used to create temporary restorations.

Fig. 3

Digital diagnostic models are also available, enabling digital forecasts (diagnostic digital "Wax Up"). This approach provides a before-and-after visualization on digital models that can then be sent for 3D printing (Fig. 4, 5). Such models are ofen referred to as demonstration, trial, motivational, or mock-up models.

Fig. 4

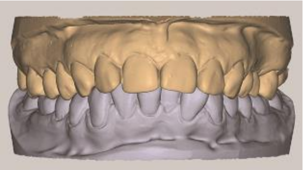

Fig. 5

Before proceeding to discuss the algorithms for manufacturing metal-free restorations, it is essential to highlight their types and the materials used.

Thus, we can obtain a 'before and after' result on digital models, which can be sent for 3D printing. Such models are also called: demonstration; trial; motivational; mock-up models.

Before starting to examine the algorithms for manufacturing metal-free restorations, let us focus on their types and the materials used for their production.

Dentists and dental technicians often face the challenge of selecting the optimal material for restoring the appearance and functional capabilities of dental arches. However, professional information can sometimes confuse not only laypeople but also specialists in the field of dentistry, as an increasing number of companies offer an expanding range of materials that allow for clinically satisfactory restorations from both aesthetic and functional perspectives. All of this significantly complicates the choice of the optimal material in each specific clinical case. To make the decision-making process regarding the use of a particular material easier, dentists and dental technicians should understand the features of available all-ceramic systems and their historical development aspects.

The production of ceramic items has been practiced by humans since ancient times. Ceramics refers to products made from inorganic materials with mineral additives through heating and subsequent cooling. The word "ceramics" itself comes from the Greek word *keramos*, which means "clay." It is likely that this word entered the Greek language from Sanskrit, where it referred to fired earth, as clay was extracted from the ground and fired to produce pottery items.

3. Dental ceramic materials

Dental ceramic materials are mixtures of non-metallic and metallic elements that form covalent bonds, creating a periodic crystalline structure. The most common types of dental ceramics consist of metal oxides (SiO_2, Al_2O_3, K_2O) and other ceramic materials, such as silicates, oxides, and their derivatives.

As a result of special processing, ionic and covalent bonds form between the individual components of the ceramic mixture, creating a cohesive structure.

Ceramic materials have long been used in dental practice, with a wide range of applications. These biologically inert materials are used for making jacket crowns, metal-ceramic restorations, inlays, onlays, veneers, and frameworks for all-ceramic constructions.

The most important qualities of ceramics include their color stability, low solubility in the oral environment, and high wear resistance.

However, despite the high compressive strength of ceramics, their use is limited by relatively low tensile strength.

When clinically applying ceramic materials, several mechanical properties are considered: flexural strength, fracture resistance, and modulus of elasticity. Flexural strength, also known as the rupture modulus, is determined by the deformation or fracture of a beam placed on two supports at its edges under central load application.

Among the types of ceramics used in dentistry today, milled zirconium oxide exhibits the highest flexural strength (990 MPa), followed by cast ceramics (378–604 MPa) and lithium disilicate pressed ceramics (350 MPa).

Fracture resistance is one of the most important mechanical properties, characterizing the brittle material's ability to resist crack formation under critical load. This index for traditional pressed ceramics is 0.78 MPa, comparable to soda-lime glass.

Lithium disilicate pressed ceramics have fracture resistance four times greater than that of pressed ceramics and twice that of leucite-reinforced ceramics.

As mentioned, another important quality is the modulus of elasticity, which characterizes the relative stiffness or rigidity of a material, determined by its bending under load. The modulus of elasticity for feldspathic ceramics is 70 GPa, for lithium disilicate pressed ceramics–100 GPa, and for milled zirconium ceramics–210 GPa.

It is also worth noting that the issue of shrinkage remains relevant for all-ceramic constructions, except for those milled from ceramic blocks that have undergone sintering. Shrinkage of milled constructions during high-temperature sintering is compensated by increasing the size of the blank using specialized software.

The coefficient of thermal expansion of ceramics based on aluminum oxide and lithium disilicate ceramics is approximately 10×10^{-6}/°C. The coefficient for zirconium oxide-based ceramics is around 10.5×10^{-6}/°C, while that for leucite-reinforced ceramics ranges from 14×10^{-6}/°C to 18×10^{-6}/°C.

It is crucial to find the correct combination between the thermal expansion coefficients of the framework and the veneering ceramic. A significant difference between them leads to delamination of the veneering ceramic from the ceramic framework.

This phenomenon is explained by the formation of compressive stress when the veneering ceramic's thermal expansion coefficient is significantly lower than that of the framework. When room temperature is reached, the framework should undergo greater shrinkage than the veneering material to minimize compression exerted on the framework. Conversely, if the veneering ceramic's thermal expansion coefficient is significantly higher than that of the framework, it may cause stress to develop within the restoration.

The ideal scenario is to achieve mild compression of the framework by the veneering ceramic at room temperature. A similar principle is used when veneering metal frameworks with ceramics.

Currently, dental professionals have access to several ceramic materials: traditional feldspathic ceramics, milled ceramics, pressed ceramics, and infiltrated ceramics.

4. Manufacturing algorithms

Among the algorithms used for creating ceramic restorations, the following can be distinguished: analog, digital-analog, and digital.

According to the analog algorithm, after tooth preparation, the dentist takes impressions using standard or custom trays. Typically, silicone, polyether, or vinyl polysiloxane impression materials are used with classical impression-taking techniques.

After transferring the impressions to the dental laboratory, a working model is created from high-strength gypsum. Depending on the chosen material and technology, the final prosthodontic construction is then fabricated.

The analog protocol does not involve the use of digital technologies at any stage.

The digital-analog algorithm allows for the use of digital technologies in transferring a negative impression (capturing an optical impression using an intraoral scanner), scanning an analog impression or model (capturing an optical impression using a laboratory scanner), and at stages of ceramic restoration production.

The digital algorithm is characterized as the most modern and rapidly developing approach. It involves the use of digital tools in both the clinic and the dental laboratory. Let’s explore it in more detail.

5. Use of CAD/CAM technology for manufacturing metal-free constructions

In the automotive and aerospace industries, computer-aided design and manufacturing have been utilized for many years. The use of computer technologies has also become an integral part of modern dental practice, although it was introduced relatively recently in dentistry. The development of precise scanning devices, software capable of accounting for material shrinkage, high-tech milling machines, and the emergence of new ceramic materials have significantly expanded the capabilities of CAD/CAM technologies.

Recent advancements in this rapidly evolving field of dentistry have reduced the time required for manufacturing prosthodontic constructions and eliminated inevitable shortcomings associated with human involvement in restoration production. Moreover, thanks to these technologies, it has become possible to fabricate durable and aesthetically pleasing ceramic frameworks with high precision.

Currently, three main methods are used for fabricating single crown and fixed partial denture frameworks:

- Manual modeling and manual production (Manual-Aided Design/Manual-Aided Manufacturing, MAD/MAM);
- Computer-aided design and computer-aided manufacturing (CAD/CAM);
- Manufacturer-specific methods (closed systems).

MAD/MAM Method

This method involves template-based milling or carving and is based on the pantographic principle, which has been used for centuries to copy or proportionally enlarge objects or images, as well as for engraving. For example, key duplicates are commonly made this way. It is believed that mechanical copying and milling can accurately reproduce the desired object.

Initially, the framework is modeled from wax or composite material, and the blank is placed into a pantograph. The copying arm of the device traces the framework blank while the milling arm, equipped with a carbide cutter, carves the object from a selected raw or pre-sintered block. The object is carved at a size 20–25% larger to compensate for shrinkage after final sintering. Each block is marked to indicate its density, which is necessary for configuring the milling device.

The equipment used for this method is relatively economical (e.g., Zirkonzahn, Ceramill by Amann Girrbach, TiZan Mill by Schutz Dental Group). Furthermore, this method allows dental technicians to correct tooth preparation defects during the wax modeling stage.

CAD/CAM Method

This approach involves three-dimensional virtual modeling of frameworks followed by automated production on a numerically controlled milling machine. Every CAD/CAM system consists of three main stages: scanning, modeling, and milling. Typically, all these stages are performed in a dental laboratory.

Closed Systems Method

This method for fabricating ceramic frameworks involves using manufacturer-specific software to transfer information to a remote milling center, where the framework is produced.

As mentioned above, milling raw blocks requires less time and results in less wear on milling equipment. Additionally, such machines are generally less expensive than those designed for processing fully sintered zirconium oxide blocks.

6. Scanning methods

Systems for computer-aided design and manufacturing of frameworks require scanning of the prepared tooth model and/or framework blank. Scanning methods vary between systems. In dentistry, the following types of scanners are used:

- Optical scanners (cameras);
- Mechanical scanners (contact digitization);
- Laser scanners;
- Light scanners using white or colored light.

In the **Cerec 3D** system by Sirona (Fig.6), an intraoral optical camera is used, which transmits a digital image of the prepared tooth and adjacent teeth.

The **Everest** system by KaVo utilizes a CCD-type (charged-coupled device) camera that creates a three-dimensional digital model after capturing images from 15 projections.

In the **Procera** system by Nobel Biocare, the working gypsum model of the prepared tooth is mechanically scanned using a spherical stylus in contact with the surface of the model. The processed information is then sent to one of the centralized milling centers for framework fabrication.

In the **Lava** system by 3M ESPE, an optical scanner (white light) is used to capture the digital image of the working model. This system allows not only prepared teeth but also all necessary anatomical contours to be scanned or copied from a virtual library.

Fig. 6

Software for Computer-Aided Design

Initially, most dental CAD/CAM systems were closed, meaning the software of a specific company was intended for use exclusively with milling equipment from the same manufacturer. This approach is inconvenient for dental laboratories as it limits the choice for dental technicians.

Currently, more manufacturers are opening their software to standard industrial formats. This means that scans performed using an open format and standard library templates can be transferred to any milling center that accepts data in standard library formats. In this case, dental technicians can choose a manufacturer depending on the required material or production method for frameworks.

An example of an open system is **Dental Designer** by 3Shape. Here, the working model is scanned using a laser and a high-resolution digital camera. Laser projections are applied to the working model, and the camera captures the image.

The operator can then sequentially design the required prosthesis using software that simulates standard dental laboratory manipulations (marking preparation margins, blocking undercuts, applying compensatory lacquer). When designing a framework for a fixed partial denture, the necessary path of insertion can be set, and telescopic caps can be created to optimize this path. The information is then sent via email to the appropriate milling center (Fig. 7).

Fig. 7

Equipment for Framework Production

Frameworks made from zirconium oxide can be fabricated in a dental laboratory or a remote milling center. The production itself is performed using either subtractive or additive methods.

The **subtractive method** involves carving the framework from a solid block. The milling duration and type of cutter depend on the block type (raw, pre-sintered, or fully sintered). The size of the milled framework is determined by the degree of subsequent shrinkage after final sintering.

The **additive method** involves applying zirconium oxide powder onto a mold. A durable mold, often metal, is created to a larger size to compensate for shrinkage during sintering. After applying the powder, it is compressed using isostatic pressure.

The raw framework is then milled to achieve the desired contour, removed from the mold, and sintered at a temperature of 1550°C.

An alternative method for ceramic framework production is under development. It is already used for creating metal frameworks and involves **selective laser sintering or melting**. Laser sintering of thin material layers allows for the rapid fabrication of three-dimensional objects of any shape with minimal raw material waste.

7. Zirconium oxide

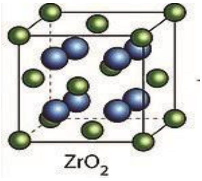

Fig. 8

The increasing popularity of zirconium oxide, which replaces metal in the production of frameworks, is notable (Fig.8). Its application exclusively relies on computer technologies, which explains the significant rise in the number of manufacturers offering software, scanners, and milling machines.

Furnaces for firing and casting have been replaced by scanners and milling machines with numerical control. Today, in the fabrication of crowns and bridge frameworks, traditional tools like burners, wax, and pressing are being replaced by keyboards and monitors. Dentists and dental technicians are now faced with an overwhelming amount of information, often leading to complications, especially as some manufacturers present incomplete or inaccurate data.

Some dentists avoid the responsibility of choosing restorative materials, leaving this decision to dental technicians. However, the dentist ultimately bears full responsibility for the prostheses placed in the patient’s oral cavity. Therefore, dentists must have a clear understanding of the materials they use in their practice. Moreover, clinicians should educate patients about the properties of various dental materials, enabling them to make informed decisions.

Considering the growing popularity of zirconium oxide, both dentists and dental technicians need to be well-versed in the mechanical and optical properties of this material. Unlike metal frameworks, zirconium oxide frameworks can be damaged, necessitating adherence to specific handling rules. While patients often choose this material for its metal-free composition, dental professionals must consider the limitations and disadvantages of alternatives to metal, including ZrO_2.

Natural Occurrence and Properties

Zirconium oxide naturally occurs in combination with silicon oxide in minerals such as zircon or baddeleyite (ZrO_2, SiO_2). It is often referred to as "ceramic steel," though the proper term is "zirconium dioxide." In English, "zirconio" is used for zirconium dioxide, "alumina" for aluminum oxide, and "magnesia" for magnesium oxide. Pure zirconium oxide does not occur naturally.

Interest in zirconium oxide as a biomaterial is due to its mechanical strength, chemical and spatial stability, and an elasticity coefficient comparable to that of stainless steel. Its normal density is 6 g/cm³, while its theoretical density (100% density) is 6.51 g/cm³. The closer these values, the less space between particles, resulting in higher strength and a smoother surface.

Crystalline Phases

ZrO_2 exists in three crystalline forms depending on the temperature:

1. **Cubic phase**: Above 2370°C, ZrO_2 is in an unstable, high-temperature cubic form with square surfaces and a density of 6.27 g/cm³.
2. **Tetragonal phase**: Between 1170°C and 2370°C, ZrO_2 is in a metastable medium-temperature tetragonal phase with rectangular surfaces and a density of 6.1 g/cm³.
3. **Monoclinic phase**: Below 1170°C, ZrO_2 stabilizes in the monoclinic phase with a parallelepiped shape and a density of 5.6 g/cm³.

From the perspective of strength, it is crucial to minimize the amount of material in the monoclinic phase. To stabilize ZrO_2 at room temperature and control phase transitions, metal oxides such as yttrium oxide (Y_2O_3) or cerium oxide (CeO_2) are added (Fig. 9).

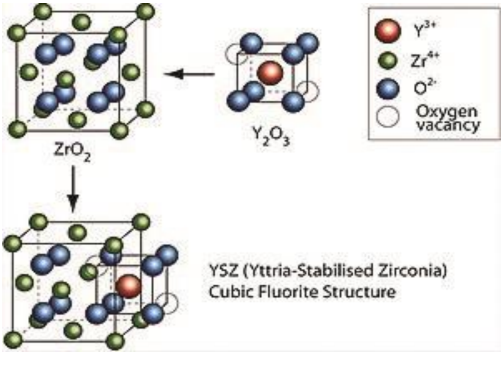

Fig. 9

Unique Features

A key characteristic of ZrO_2 is its ability to resist crack propagation through **transformation toughening**. This process involves a phase change from tetragonal to monoclinic, resulting in a 3–5% volume increase around crack edges. This creates compressive stress that counteracts tensile forces at the crack boundary, contributing to the material's wear resistance and flexural strength of 900–1200 MPa.

Manufacturing Blocks

ZrO_2 is supplied to dental laboratories in blocks of various sizes for milling frameworks of single crowns or partial fixed dentures. These blocks are produced using two main methods:

1. **Uniaxial semi-dry pressing**: Pressure is applied in one direction to ceramic powder in a mold, creating a "green stage" material. The process can result in uneven material density due to particle friction. Blocks produced by this method are typically square or rectangular.
2. **Isostatic pressing**: The powder is placed in an elastic mold and subjected to uniform pressure in all directions, creating a chalk-like block with uniform density. These blocks are generally cylindrical.

After initial pressing, the blocks are stabilized and densified through firing in specialized furnaces, achieving 95% of the theoretical density. This stage is referred to as "pre-sintered." Further compression and firing enhance strength and remove residual porosity through **hot isostatic pressing**.

Types of Blocks

1. **Raw blocks** are milled at larger dimensions to compensate for 20–25% shrinkage during final sintering. These blocks are porous, easier to mill, and cause less tool wear.
2. **White blocks** have undergone hot isostatic pressing and are milled to precise dimensions.

Manufacturers

Manufacturers offering raw blocks include: Cercon (Degudent); Lava (3M ESPE); DigiDent (Girrbach).

Pre-sintered blocks include:Vita In-Ceram YZ Cubes (CEREC Inlab); KaVo Everest ZS-Blanks (KaVo); Hint-Els Zirkon TZP-W (Girrbach).

White blocks include: Denzir Premium HiP Zirconia (Etkon) ; Hint-Els Zirkon TZP-HiP (Girrbach).

CONCLUSIONS

The development of digital technologies, in general, and dental digital protocols, in particular, not only raises public awareness about health and appearance but also significantly increases the aesthetic demands of patients. Today, patients desire not only functional but also beautiful, aesthetically pleasing restorations that are indistinguishable from natural teeth.

The continuous evolution of digital technologies and their application in clinical dentistry has enabled dental treatment to become less invasive and relatively straightforward.

The use of digital technologies for manufacturing metal-free restorations, along with their constant improvement, demonstrates characteristics of systematically managed development. This manageability is based on a systematic approach and modern information technologies, which allow for rapid modeling of various developmental pathways, precise forecasting of outcomes, and the selection of the most optimal solutions.

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