



Computer-aided design and manufacturing of dental surgical guides based on cone beam computed tomography

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ABSTRACT

Purpose: The aim of the paper is to present the own method of design and manufacturing of surgical guides on the basis of cone beam computed tomography (CBCT) scans and three-dimensional models of teeth and soft tissue obtained from impressions or intraoral optical scans, which are possible to use during surgical implant placement.

Design/methodology/approach: The method of designing and manufacturing of surgical guides was developed on the basis of real clinical data coming from patients with severe bone deficit qualified for implantological treatment. The model of bone and virtual model of soft tissues were combined together. The project of the prosthetic restoration imposed on the virtual model of the bone was used to plan the position of the implants. The final surgical guide was manufactured with the use of a CNC milling machine.

Findings: The method enables planning of the implant position based on two combined models of the bone and soft tissues and allows to design and manufacture a surgical guide. Thus, it becomes possible to place the implants in the bone of the patient during a surgical procedure in a preplanned position.

Practical implications: Thanks to the method of designing and manufacturing of surgical guides a range of clinical tasks in preparation of the guides is restricted to registration of the intraoral situation, taking of CBCT scans of the bone and determination of the type of the prosthetic restoration. Properly made surgical guides allow to shorten the time of the surgical procedure and carry it out in a minimally invasive manner.

Originality/value: This paper presents an original method of designing and manufacturing of surgical guides. This allows for precise planning of the position and the number of implants and the transfer of these data into the mouth of a patient during the surgery without the use of commercially available closed software.

Keywords: Surgical guides; Guided surgery; Dental implants; Cone beam computed tomography

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

There has been a significant increase of interest in implantoprosthodontic rehabilitation of the stomatognathic system for the last three decades [1]. This is due to the fact that a prosthesis supported by implants provides a significant comfort for the patient resulting from the transfer of occlusal forces directly on bone rather than on the oral mucosa or the periodontium of the adjacent teeth [2].

The crucial prerequisite to start implant prosthetic rehabilitation of the patient is the presence of sufficient volumes of alveolar bone, enabling to place the implant in the bone and to obtain primary implant stability. The stabilization of the implant determines the undisturbed process of osseointegration, resulting finally in its ability to transfer significant occlusal loads in the repeated cycles over a number of years [3]. Ensuring proper stabilization, undisturbed osseointegration and long-term function of the implant subjected to occlusal loads requires sufficient amounts of alveolar bone surrounding the implant. It is assumed that these conditions are met when the layer of bone tissue surrounding the implant is at least 1.0mm [4]. It must be observed that there is a number of sensitive structures in the proximity of the alveolar ridge that cannot be damaged either during preparation of the implant bed, or during the placement of the implant. These structures include the maxillary sinus and the nasal cavity in the maxilla and the inferior alveolar nerve running in its canal in the mandible providing sensory innervation for lower teeth, gums and the lower lip [5].

Therefore, in the process of implant treatment planning it is extremely important to assess the bone anatomy to ensure the proper implant placement in the bone tissue and avoid any damage to sensitive anatomical structures. In the recent past standard radiograms, including dental intraoral x-rays and orthopantomogram were used to assess the bone anatomy [6]. This examination provided an opportunity for the two-dimensional assessment of the bone in the vertical and transversal dimensions. It was not possible to evaluate cross sections of the alveolar bone. This evaluation was made applying time-consuming and invasive to some extent procedures of so called "bone-mapping". These procedures were carried out on plaster models obtained from intraoral impressions. The models were cut crosswise at the site of the planned implantation. To determine the thickness of the mucous membrane covering the alveolar ridge a sharp instrument was used to pierce the mucosa at the site of the planned implantation in such a way that the end of the tool touched the surface of the bone. After measuring the length of the tool engaged in the gum, this

measurement was marked on the cross section of the cast. In this way the cross-sectional image of the alveolar bone was obtained [7]. Another way to measure the width of the alveolar ridge was to measure it directly during surgery. Applying this method, it was not possible to select the implants of a certain diameter and length before the surgery, and in some cases when there was insufficient amount of bone in the transversal dimension, the surgery needed to be stopped.

Currently, in order to evaluate the anatomy of the bone three-dimensional (3D) computed tomography (CT) or cone beam computed tomography (CBCT) are often used [8]. Modern dental practices are now often equipped in CBCT x-ray units. In CBCT machines one source emits x-rays in the direction of the patient's facial cranium and a set of minimum 3 detectors receives radiation that has not been absorbed by the patient's body. The data obtained in this way are saved in DICOM format files (Digital Imaging and Communications in Medicine). During the examination the unit acquires from 100 to 500 two-dimensional images representing different layers of the entire 3D image, usually along Z axis. The standard resolutions of the CBCT machines are within the range of 100-300 microns due to limitations in the construction of detectors. Due to the additional processing of the image in post-production it is possible to achieve higher resolutions, but in most cases the image quality is poor. This resolution is sufficient for diagnosis in almost every case and enables a medical practitioner to plan any surgery and to verify the effects of treatment during and after its completion. The created file contains the values of radiation that reached the detectors, which are processed to be displayed in grayscale using the tables of conversion of useful values (VOI LUT). They provide definitions of the data module, which matches the values stored to those that are to be displayed on the screen [9]. Based on data from CT and CBCT it is possible to obtain three-dimensional reconstructions of the implantation site and to carry out measurements of available bone in all cross-sections. Thanks to the possibilities of modern software, it becomes possible to plan both virtual implant placement, as well as the future prosthetic suprastructure [10].

With the development of imaging techniques and modern software the concept of implant treatment planning has changed. Formerly, the planning was subordinated to the surgery (surgically-driven implantology) and the implants were inserted at the sites where sufficient amount of bone was available. Doing so, however, it encountered considerable difficulties in prosthetic phase of treatment, since the position of the implants did not always correspond to the demands of a prosthetic superstructure. In many cases it was necessary to take out the implant or

redesign planned prosthesis. Currently, the planning is dominated by the demands of the prospective suprastructure (prosthodontically-driven implantology). In this method, firstly the proposed prosthetic restoration is designed, and only then, with the virtual planning, the position of the implants is planned. The position is the most favorable from the prosthetic point of view [11].

The problem with this method is the transfer of virtually planned position of the implants to the actual conditions during the implantation procedure. To enable the transfer of the information about the implant position to the surgery, the surgical guides are produced. The implant position is planned virtually on the basis of the image of the bone from CBCT and the configuration of the intraoral soft tissue and optionally the residual dentition of the patient acquired from plaster casts or intraoral scans. Surgical guides include tunnels for carrying the drill in a specific 3D orientation and optionally they have holes for securing the template in the mouth with screws. Templates are installed in the oral cavity at the start of surgery. Then, the implantologist introduces successively burs of increasing diameter to the pilot holes of the guide template preparing the implant beds [12].

Despite permitting the preparation of the bed for the implant in a pre-planned 3D configuration, the guides also change the technique of the surgery. The use of surgical guides significantly shortens the surgery time. In addition, no preparation of muco-periosteal flaps is needed any more to enable the direct access and visual inspection of the surface of the bone. The treatment can be carried out by flapless technique, reducing significantly the postoperative discomfort [11-13].

The aim of the paper is to present the own method of designing and manufacturing of surgical guides on the basis of cone beam computed tomography (CBCT) scans and three-dimensional models of teeth and soft tissue obtained from impressions which are possible to use during surgical implant placement, especially in difficult clinical situations characterized by significant bone loss.

2. Clinical case presentation and methodology

2.1. Clinical case presentation

The method of designing and manufacturing of surgical guides was developed on the basis of real clinical data coming from a patient with severe bone deficit in the maxilla qualified for implantological treatment. The patient

was a 55-years-old woman referred for implant rehabilitation. She was a healthy, non-smoking individual. She had been wearing an upper removable denture for many years. The denture was not stable enough to provide sufficient comfort to the patient. The patient presented periodontally compromised teeth 13 and 16 that were beyond salvation. The natural dentition in the lower jaw enabled successive restoration of the occlusion after completion of the treatment on the maxilla. X-ray examination including CBCT revealed significant bone loss of the maxilla and massive pneumatization of the maxillary sinuses bilaterally (Fig. 1, 2).



Fig. 1. OPG of the patient showing non-restorable teeth 16 and 13, massive bone loss of the maxilla and pneumatisation of the maxillary sinus bilaterally



Fig. 2. Three-dimensional reconstruction obtained from CBCT

The treatment plan agreed with the patient included the removal of periodontally involved teeth 16 and 13, the maxillary sinus floor elevation with cancellous bone graft

from the tibia mixed with a xenograft bilaterally and placement of 6 intra-osseous implants loaded with a fixed prosthesis or a bridge.

The procedure of bilateral sinus-lift with the autograft from the tibia was carried out in the hospital under general anaesthesia (surgeon - prof. Piotr Malara) according to surgical methodology described previously [14]. After the time of the graft healing a control CBCT was taken that revealed sufficient bone volume for implant placement at the back regions of the maxilla (Fig. 3 and 4). Because of very difficult anatomy it was decided to prepare surgical guides for the implant placement.



Fig. 3. OPG of the patients taken 6 months after the sinus-lift procedure

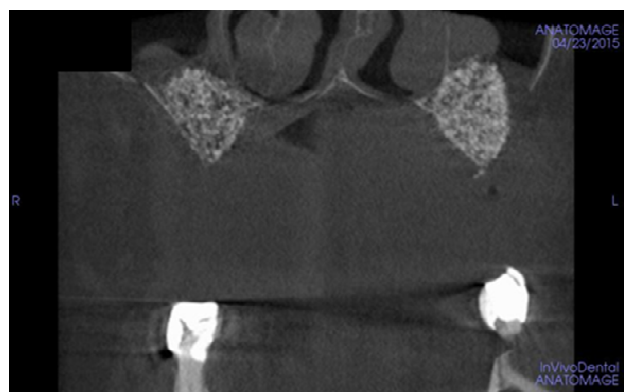


Fig. 4. A frontal section of the maxillary sinuses revealing sufficient bone volume for implant placement

2.2. Methodology of designing and manufacturing of the surgical guides

The goal of the method was to prepare the surgical guide based solely on the data from CBCT scans and the information about configuration of the soft tissues of the oral cavity achieved from intraoral impressions. A tomogram contains information describing the space in the shape of a cylinder of a specified size (in our case it is a cylinder with a height of 6 cm and a diameter of 4 cm)

containing data describing both the space around the patient, and information on the soft tissues and the bone. To plan the position of the implants, the acquired in the DICOM format image was subjected to filtration before creating the three-dimensional model in order to select for further processing the area of the bone. Filtration was done by analyzing the image histogram, which is a vector with a number of elements equal to the number of existing levels of brightness and the following elements of the histogram $hist(q)$ determine the cardinality of the pixel brightness q (Fig. 5, 6). After extracting the area of interest and a visual inspection of the displayed data a three-dimensional model in the format stereolithography (STL) was generated, which is widely used in manufacturing procedures including the procedure of CAD/CAM used in this case (Fig. 7). Files saved in STL format describe the shape as a grid of triangles with a predefined deviation, which should be lower than the minimum precision of the manufacturing machine used to produce the final product. The optimal position of the implants in the surgically reconstructed bone was planned on the obtained three-dimensional model of the bone (Fig. 8).

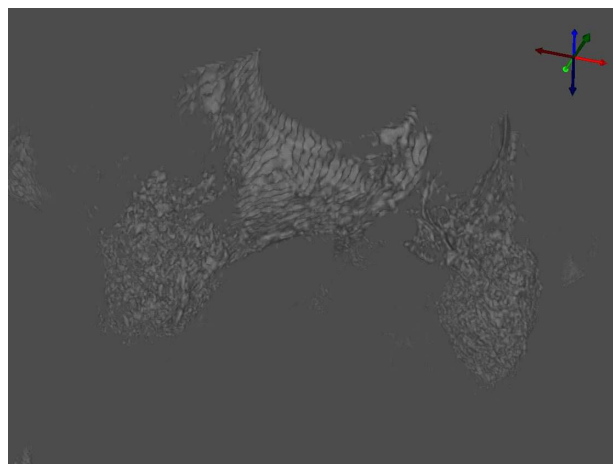


Fig. 5. Reconstruction of a 3-D image of the bone by manual adjusting of the histogram under visual supervision

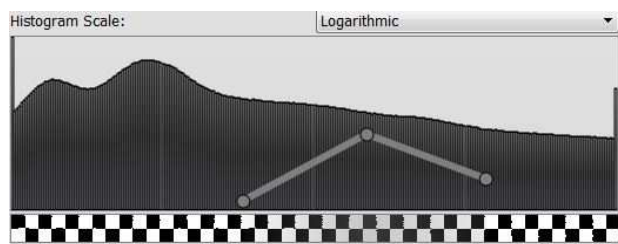


Fig. 6. A histogram scale used for the reconstruction of a 3D image of the bone

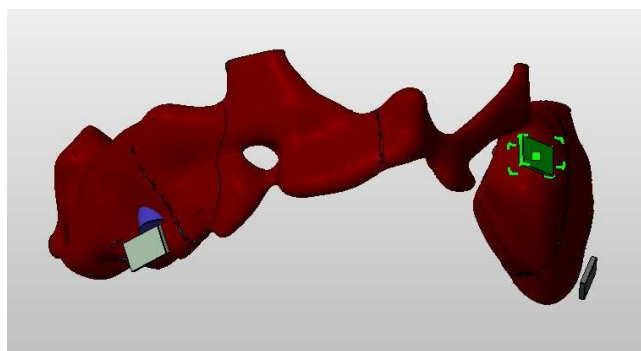


Fig. 7. STL model of the bone with markers used for further processing

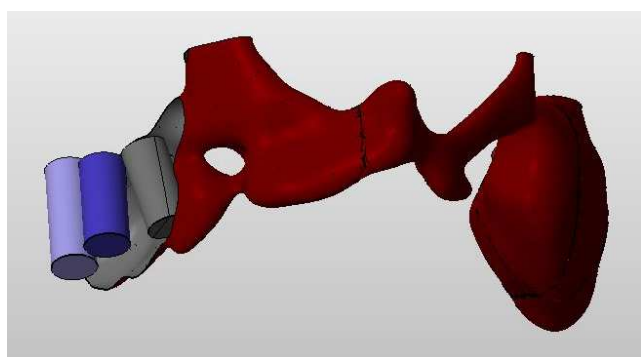


Fig. 8. STL model of the bone with the planned position of the implants on the right

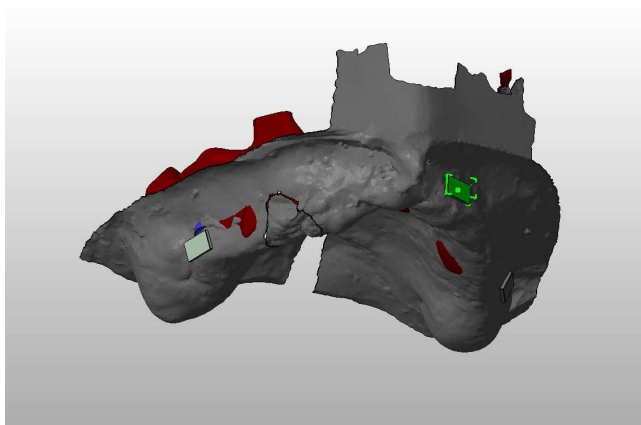


Fig. 9. The model of the soft tissues superimposed on the model of the bone

To ensure secure fastening of future template in the mouth, as well as to carry out the procedure for the design of the restoration, it was necessary to reconstruct the three-

dimensional implant area when viewed from the mouth. For this purpose, a three-dimensional model of soft tissues in stereolithography format was created. A plaster model was made on the basis of intraoral impressions and scanned with a laboratory optical scanner. An important element at this stage was to ensure a proper connection between the model of the bone and the model of the soft tissue. Markers which are visible both on the model made on the basis of the tomogram, and on scans of a plaster cast were used for this purpose. It was important to ensure a stable position of the markers during scanning (Fig. 9). In this method three markers were used.

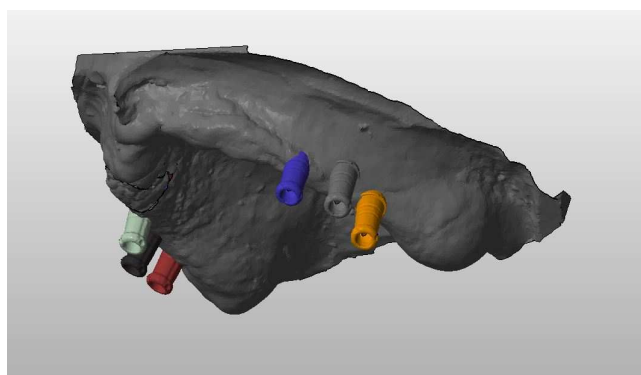


Fig. 10. Images of scan-abutments retrieved from the database of the design software attached virtually along the long axis of the implants and protruding over the model of the soft tissues

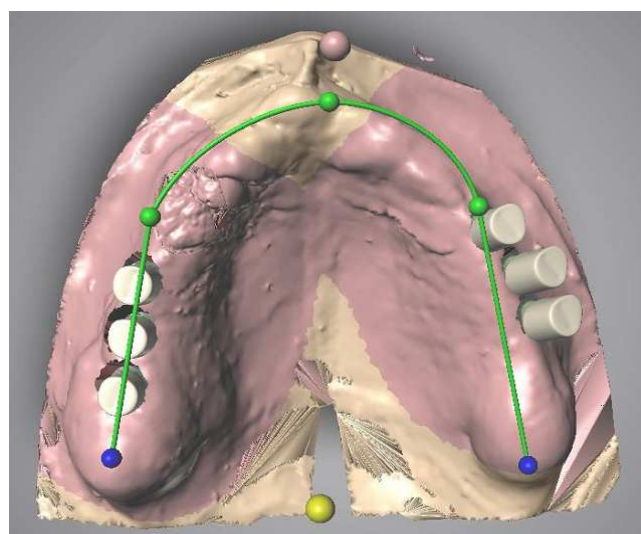


Fig. 11. The design of the shape of the dental arch of the prospective prosthetic restoration

The models with visible markers prepared in this way were linked together using the design software. At this stage the previously planned position of the implants in the three-dimensional model of the bone was verified. For this purpose, images of scan-abutments retrieved from the database of the design software were attached virtually along the long axis of the implants protruding over the model of the soft tissues (Fig. 10).

After positive verification of the position of the implants a shape of the dental arch was designed (Fig. 11) as well as the shape, size and position of the artificial teeth in the prospective final prosthetic suprastructure (Fig. 12).

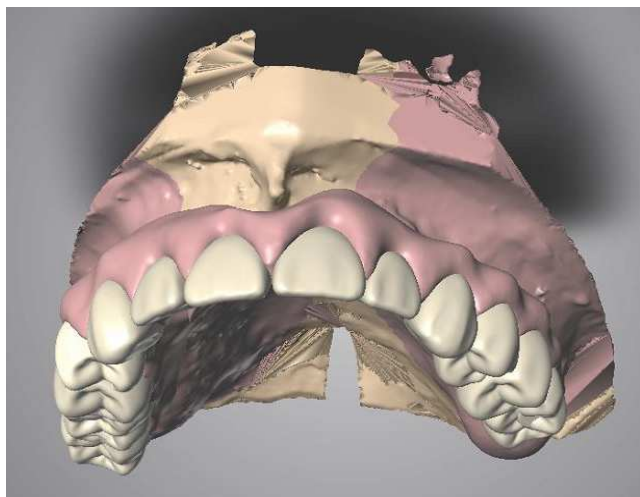


Fig. 12. Design of the teeth alignment in the final prospective prosthetic restoration

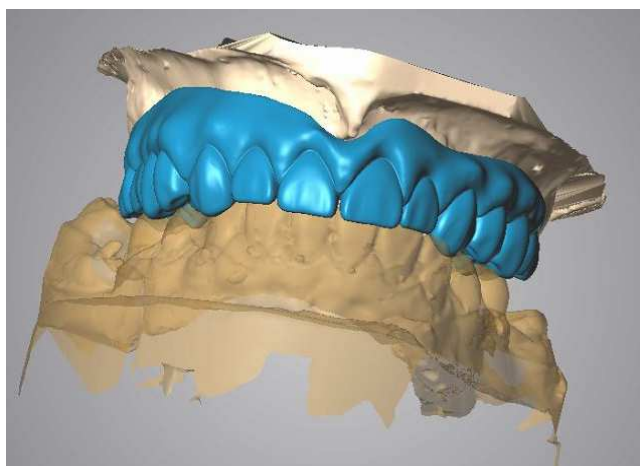


Fig. 13. Virtual check of the designed prosthetic restoration in relation to the opposing teeth

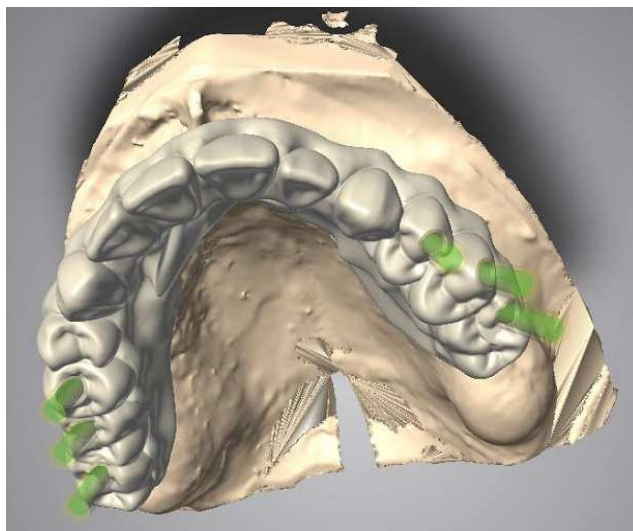


Fig. 14. The design of the final shape of the surgical guide



Fig. 15. Milling of the surgical guide in the CNC milling machine

At this stage the designer (Mr. L. B. Dobrzanski, MSc. Eng.) made a project of the prosthetic restoration taking into account the prevailing conditions in the patient's mouth and using libraries of shapes of teeth in the design software. Characteristics of the materials from which the final restoration will be made must be taken into account at this point. The minimum thickness of the material layers must be maintained at every point of the permanent restoration. Then, the designed dental arch was set against the model of the opposing teeth to verify the occlusion (Fig. 13).

Following the positive verification of the final prosthetic superstructure, the final shape of the surgical guide was developed. It took into account the guiding channels for the surgical bur that would be used during implant placement in accordance with a pre-planned position (Fig. 14). To manufacture the surgical template polymethyl methacrylate (PMMA) was selected. The final surgical guide was prepared by milling it in a computer numerical control (CNC) milling machine (Fig. 15).

The manufactured surgical guide (Fig. 16) was used during surgery to place 6 implants. The OPG taken postoperatively showed the correct placement of the implants at the area of the bone reconstructed previously (Fig. 17).



Fig. 16. The physical surgical guide ready to use intraorally during implant placement



Fig. 17. The control OPG x-ray taken after implant placement

3. Discussion

A common use of the CBCT results in exploring further applications for the information about the state of the

patient's tissues is planning and execution of implant treatment [8, 12]. A particularly important issue is to plan the placement of implants in the available bone to ensure their optimal location allowing the execution of fully cosmetic prosthetics. In such a context it is important to position the implants in the way that the attached implant abutments were placed within the light of a dental crown and not in the interdental spaces. Clinical experience shows that when the implants are placed in interdental positions a higher rate of periodontal complications occurs and the aesthetic result of the final restoration is often compromised [15]. In addition, an extremely important issue in the planning of the prosthetic reconstruction of the whole arch is the possibility to visualize the prospective results of the treatment to the patient at the beginning of the diagnostic process. Responding to the needs described above it is advisable to produce a surgical guide mirroring the shape of the teeth in the prospective restoration and allowing the implantologist to place the implants in the pre-planned position [11].

Designing and manufacturing of a surgical guide requires close collaboration of an implantologist with an engineer of dental engineering in the following aspects of the workflow:

- determination of anatomical areas where dental implants can be placed,
- creation of a three-dimensional model of the bone based on CBCT scans,
- creation of a three-dimensional model of the natural teeth and soft tissues of the oral cavity on the basis of intraoral impressions or intraoral scanning,
- linking of the three-dimensional model of the bone and the three-dimensional model of the oral cavity,
- designing of the prosthetic restoration on the basis of the three-dimensional model of teeth and soft tissues in the mouth and choice of materials for manufacturing of the restoration;
- planning the position of the implants based on the model of the bone and the model of predicted prosthetic restoration;
- planning the technological holes for running a pilot-drill used for implant bed preparation;
- designing of the final shape of the surgical guide;
- the choice of material from which the surgical guide will be made;
- manufacturing of the surgical guide using a computer numerical control milling machine.

In the process of designing and manufacturing of the surgical guides a very important role of a dental engineer - a designer includes solving of the following tasks:

- a correct creation of a 3D model of the bone based on the tomogram - the correct selection of parameters and generating the model so that it can be linked with the model of soft tissues and teeth,
- verification of the treatment plan presented by an implantologist in terms of mechanical strength of the prospective restoration and available materials;
- the correct planning of the implant position based on two models - the model of the bone and the model of the soft tissues and natural teeth;
- choice of a material to produce the surgical guide;
- execution of the manufacturing of the template in CAD/CAM technology.

In the described method the range of clinical tasks in preparing the surgical guide is limited to assessing the situation in the mouth and evaluation of the quality of the available bone during qualification of the patient for implant treatment and determination of the preliminary choice of the final prosthetic restoration (fixed or removable) supported by a certain number of implants.

An important task of contributing to the proper execution of implant treatment is the selection of appropriate materials, both to manufacture the final prosthetic construction, as well as the surgical template [16].

A prosthetic suprastructure can be milled from a chrome-cobalt alloy covered with porcelain, colored monolithic full-contour and all-ceramic zirconium dioxide or zirconium dioxide covered with porcelain in the case of fixed restorations. It may also be milled from polymeric materials used mainly in implant-supported removable restorations. In order to ensure sufficient mechanical strength under conditions of reproducible occlusal loads full-contour restorations made of zirconium dioxide should not reach anywhere thickness of less than 0.5-0.6 mm, the veneered restorations on zirconium dioxide should not be thinner than approx. 1-1.2mm and the veneered prostheses on the chromium-cobalt alloy should not reach a thickness of less than 1mm [17, 18, 19].

During the treatment planning it must also be decided whether it is necessary to restore the soft tissues and teeth or just the teeth, and also specify the intended shape and size of the teeth. At the same time, it must be determined how to fix the final restoration to the implants. In the case of screw retained restorations on the implant level it is necessary to plan the placement of the implants parallel one to another and as close as possible to the vertical axis of the tooth in the restoration. In the case of difficult bone conditions, it is possible to use cement-retained suprastructures. The last option is the use of special angle mounting screws. Such a solution, however, requires the

use of switches with a larger diameter and cannot always be applied. The decision on the final fixing of work should be decided on the basis of the possibility of implantation in each individual case at the stage of preparing a surgical guide [20].

An engineering problem remains also the choice of a material to manufacture the surgical guide. For technological reasons, particularly the time needed to complete such a guide, two materials are considered. The first is PMMA, in which the pilot tunnels must be covered by dedicated to the implant system a steel sleeve in order to prevent penetration of cuttings of the material to the implant bed in the bone. The second solution is to make surgical template out of zirconia. The second solution allows to manufacture the whole template as a monoblock with a minimal risk of contamination of the implant bed with chips produced as a result of accidental touching the walls of the guide with a drill. This solution also allows to achieve greater precision of the manufacturing guide [16].

It should be emphasized that the work described in this innovative method of preparing surgical guides allows for their completely virtual design based only on data from computed tomography and information on the intraoral situation based on impressions. So far the most commonly used methodology consists of preparing first physical restoration made of X-ray absorbing material and then performing two tomographic studies. The first examination is performed with the scan-prosthesis in the patient's mouth. Then only the scan-prosthesis is subjected to X-ray examination. The linkage of both CBCT scans allows to obtain information on available bone in relation to the planned prosthetic restoration in the mouth [21]. The use of the own methodology of design and manufacturing of surgical guides is limited at the moment to determine the path of insertion of implants only. Expanding the abilities of the guides to control the preparation depth requires the development of special drills dedicated to a specific implant system and to carry out laboratory and clinical studies evaluating the maximum deviation of the apex of the implant inserted into the bone in relation to the virtually planned position.

It should be noted that a properly prepared surgical guide will certainly help accelerate the implantation procedure and reduce its invasiveness, thereby reducing patient recovery time. Thus, it appears advisable to design and manufacture this type of guides and optimization of the process surely will enable a spread of their applications. The surgical guide may fulfill two tasks. The first and the most important of them is simplification of the implant placement in very difficult cases resulting from significant bone loss. The second task of the guide is to show the

patient the prospective effect of the treatment at the beginning.

4. Conclusions

The developed method enables the proper planning of the implant position based on two combined models of the bone and soft tissues and allows to design and manufacture a surgical guide. Thus, it becomes possible to place the implants in the bone of the patient during a surgical procedure in a pre-planned position. Thanks to the presented method of designing and manufacturing of surgical guides a range of clinical tasks in preparation of the guides is restricted to registration of the intraoral situation and taking of CBCT scans of the jaw bone as well as determination of the type of the prosthetic restoration. Properly made surgical guides allow to shorten the time of the surgical procedure and carry it out in a minimally invasive manner.

Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

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