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A new technique for the creation of a higher accuracy 3D geometrical model of the human masticatory system

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1. Introduction

The human masticatory system from biomechanical point of view can be described as a complicated combination of several paired anatomically complex muscles and jaws supported by two interlinked joints. Analysis of mandibular biomechanics helps to understand the interaction of form and function, and also aids in the improvement of the design and the behavior of restorative devices placed on the jaws structures for rehabilitative purposes, thus increasing their treatment efficiency [1]. The number of direct studies of masticatory system is limited, because its components are difficult to reach and the applications of experimental devices inside the structure introduce damage to its tissues, which influence their mechanical behavior [2]. Most of indirect studies are based on creation of biomechanical representations of the system, i.e. modeling. The majority of earlier described mathematical models of masticatory system represent just several individual parts of the system, such as temporomandibular joint [3], upper jaw [4], single teeth [5, 6] or their supporting tissues [7, 8]. Low accuracy of geometrical form reconstruction [9] and high irradiance doses of computed tomography scanning are the main limitations of recently published studies describing attempts of mathematical modeling of entire masticatory system [10, 11].

The objective of this study was to develop technique for creating three-dimensional model of human masticatory system, characterized by high accuracy of surfaces geometry reconstruction, enabling definition of system elements by three-dimensional coordinates and effective irradiance dose reduction for the investigative person.

2. Measurements of the hard tissues geometry

To get information about geometry of hard tissues of masticatory system computed tomography scanning was performed in Clinic of Radiology (Kaunas University of Medicine). Material of the research was one cadaver of 20 year old man without lesions in tissues of masticatory system. The research protocol of this study was approved by Committee of Bioethics (Kaunas University of Medicine). Multisection spiral computed tomography was performed (Light Speed Pro 16, General Electrics, USA) of the area from infraorbital region to the base of mandible. During the examination the subject's head was fixed so that central facial line would coincide with sagital plane; the mandible was depressed and fixed to avoid the overlay of dental arches. Computed tomography scanning protocol and reconstruction parameters are presented in Table 1.

Primarily survey scanning of all area from infraorbital region to the base of mandible was done and the area of 1276×1276 mm was examined within slice thick-

Table 1

Computed tomography scanning protocol and reconstruction parameters

Parameter	Survey scanning	Fragment scanning
Device	Light Speed Pro 16, GE	Light Speed Pro 16, GE
Scanning mode	Multisection, spiral	Multisection, spiral
Tube voltage, kV	140	140
Tube current, mA	100	100
Exposure time, s	0.4	0.4
Table movement speed, mm/s	1	1
Slice thickness, mm	1.25	0.625
Image number	103	1397
Scanned area size, mm	1276×1276	96×96
Image size, pixels	512×512	512×512
Min pixel size, mm	2.49×2.49	0.134×0.134
Min Z interval, mm	1.3	0.06125
Absorbed irradiance dose, mGy	411.69	1225.05
Effective irradiance dose, mSv	0.97	2.81

ness of 1.25 mm; in result 103 images of slices within-thickness of 1.25 mm were obtained (Fig. 1). The effective irradiance dose was 0.97 mSv. The survey scanning gave information about spatial arrangement of all the hard components of masticatory system due to accurate three-dimensional coordinates of each slice.

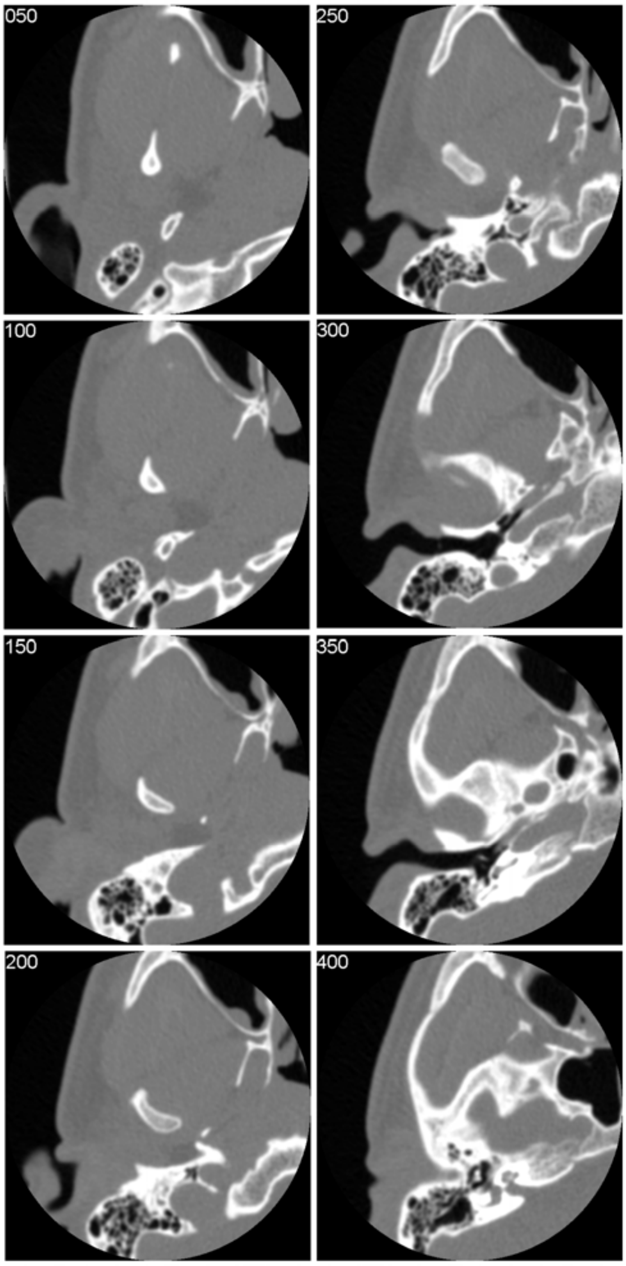


Fig. 1 Two-dimensional images of left temporomandibular joint achieved by survey computed tomography scanning.

In this study we aimed to get high accuracy images, so fragment scanning of all principle elements of masticatory system was performed to achieve the highest possible image resolution. The fragment scanning of four specific areas (upper and lower dental arches, right and left temporomandibular joints) was performed on minimal possible for this device view field of 96×96 mm within minimal possible slice thickness of 0.625 mm; that type of scanning delivered 1397 high resolution images (Fig. 2).

Total effective irradiance dose of four areas fragment scanning was 2.81 mSv. In total 1500 two-dimensional images were registered, total effective irradiance dose during the examination was 3.78 mSv; total absorbed dose was 1636.74 mGy. During survey scanning the area of 1276×1276 mm was examined, in obtained two-dimensional images 1 pixel described area of 2.49×2.49 mm. Whereas fragment scanning was done on minimal possible for this device view field of 96×96 mm and the area of 0.134×0.134 mm was described by 1 pixel in obtained images. Due to the fragment computed tomography scanning resolution of obtained images increased approximately 18.6 times, hence it was possible to reconstruct higher accuracy geometrical form of investigated structures if compared with survey scanning method.

Fig. 2 Two-dimensional image of mandible achieved by fragment computed tomography scanning

All of scanned fragments had accurate three-dimensional coordinates which were designated automatically for each slice. Based on these coordinates' higher accuracy fragments were associated into one entirety together with lower accuracy fragments of upper and lower jaws according to general system of axes. Consequently real spatial arrangement of system's elements was preserved and maximal possible for used device accuracy two-dimensional images necessary for creation of three-dimensional model were obtained.

Because of insufficient resolution of computed tomography scanning, especially for occlusal surfaces of teeth, complementary optical scanning was done in order to increase accuracy of occlusal surfaces reconstruction. Materials of the study were gypsum casts of the upper and lower dental arches, made by alginate impressions of the dental arches of the investigative cadaver. Three-dimensional specialized optical scanner (author – Prof. R. Šurna, KTU, Lithuania) was used to determine zones of optical brightness on the gypsum models of upper and lower dental arches.

Three dimensional optical scanning was implemented using video camera and controllable XYZ coordinate table. Algorithms for table control, views formation and registration, optical slices processing, surface's coordinates measurement and formation of data array were made using professional software Image-Pro Plus (Media-Cybernetics, Inc. JAV, www.mediacy.com). Discretion step of the three dimensional optical scanner was programmed. Scanning of the gypsum models of dental arches was performed with discretion step of 50 micrometers in X and Y directions and 25 micrometers in Z direction. Frame size of refrigerant 12 bit camera was 1392×1040 view elements, the lens and optical system of the scanner allowed scanning zone of 2, 3 teeth simultaneously. In received images 1 pixel described area of 0.05×0.05 mm, therefore, accuracy of reconstruction of teeth occlusal surfaces increased approximately 2.7 times if compared with fragment computed tomography scanning.

Objectives of this study were not only to increase accuracy of surfaces reconstructions but to minimize irradiance dose for investigative person substantially to apply the methodology for live human. Our original hybrid modelling methodology allows to reduce irradiance substantially by using lower accuracy computed tomography survey scanning for the estimation of bony surfaces parameters and spatial arrangement of masticatory system's parts; and high accuracy models of dental arches can be created by optical scanning data of gypsum casts of dental arches. In this study we tested such hybrid methodology and estimated that effective irradiance dose decreased from 3.78 to 0.97 mSv and was close to average effective dose of standard spiral computed tomography scanning of head (0.93 mSv); the minimal area of reconstructed elements decreased from 0.134×0.134 to 0.05×0.05 mm; hence, the accuracy of reconstruction of teeth occlusal surfaces increased approximately 2.7 times without an increment of irradiance effective dose. The main parameters of three different scanning techniques used in our study are presented in Table 2.

Table 2

Comparison of parameters of three scanning techniques

Technique	Minimal pixel size, mm	Effective irradiance dose, mSv
Survey computed tomography scanning	2.49×2.49	0.97
Combined survey and fragment computed tomography scanning	0.134×0.134	3.78
Combined survey computed tomography scanning and optical scanning of casts of dental arches	2.49×2.49 (bony surfaces) 0.05×0.05 (teeth surfaces)	0.97

3. Formation of geometrical models

Based on two-dimensional images of hard tissues of human masticatory system, obtained by means of computed tomography scanning, three-dimensional geometrical models of all components comprising the biomechanical system were created using the Image Pro Plus 5.1 software (Media Cybernetics, USA) and Imageware 11 software (Electronic Data Systems Corporation, USA). The algorithm of generating the geometrical model consisted of the following stages: (1) finding the coordinates of surface points of each individual element from raster environment in tomography sections; (2) processing of point coordinates – point clouds; (3) description of elements surfaces by finite elements – polygons; (4) minimization of description by polygons; (5) description of surfaces by splines. Three-dimensional geometrical models of hard parts comprising the masticatory system (mandible, mandibular and maxillary dental arches, mandibular condyles and mandibular fossae of temporal bones) were formatted based on the information obtained from computed tomography two-dimensional images and associated into one entirety according to accurate three-dimensional coordinates and general system of axes [12] (Fig. 3, 4).

The main limitation of geometrical model based on computed tomography scanning data is insufficient accuracy of teeth occlusal surfaces reconstruction. The higher accuracy three-dimensional geometrical models of the upper and lower dental arches were created by means of Image Pro Plus 5.1 software (Media Cybernetics, USA) based on the obtained data of optical three-dimensional scanning of gypsum casts of dental arches.

In this study we aimed not only to increase the accuracy of three dimensional model of the investigative object, but also to minimize its description by rational primary processing, minimizing the influence of scanner's interferences and micro-irregularities of the gypsum

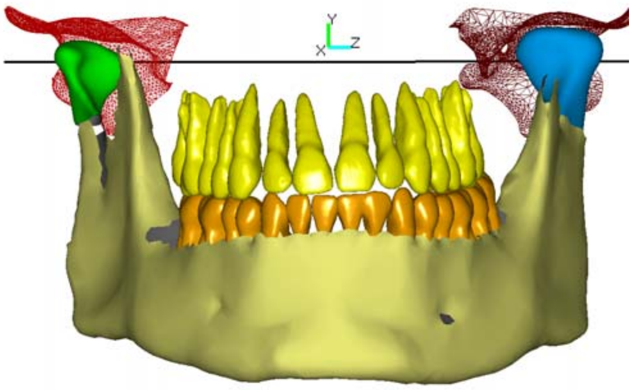


Fig. 3 Three-dimensional geometrical models of hard elements of masticatory system (frontal view)

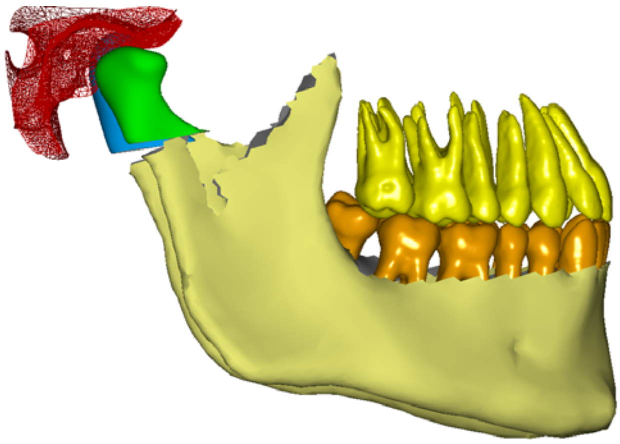


Fig. 4 Three-dimensional geometrical models of hard elements of masticatory system (lateral view)

models of the dental arches, minimizing size of data array, describing the model. Measurement of the object's surface coordinates with three dimensional scanner results in point cloud processing. Having the point cloud, the surface of the model is formed of the finite elements – polygons. Figures 5 and 6 allow comparison of two teeth models created by two different scanning systems – optical scanner and computed tomography scanning – data. Due to several times higher resolution occlusal surface of gypsum model of dental arch scanned with the three dimensional optical scanner, has considerably higher frequency dimensional constituents.

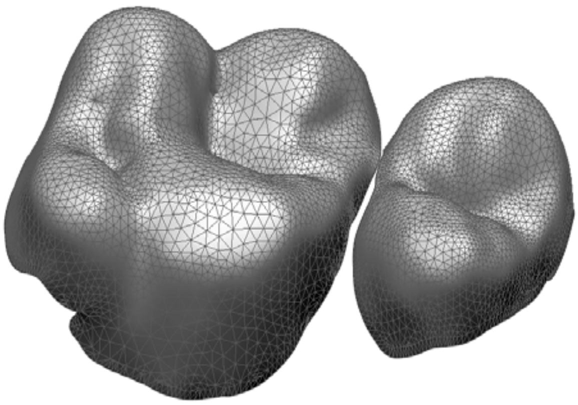


Fig. 5 Models of occlusal surfaces of two teeth, created by data of three dimensional optical scanner

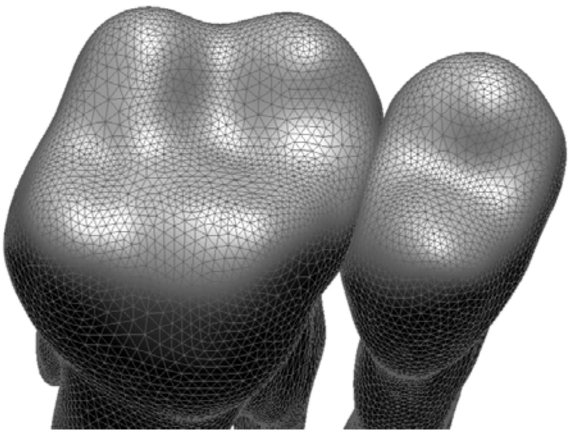


Fig. 6 Models of occlusal surfaces of two teeth, created by data of computed tomography scanning

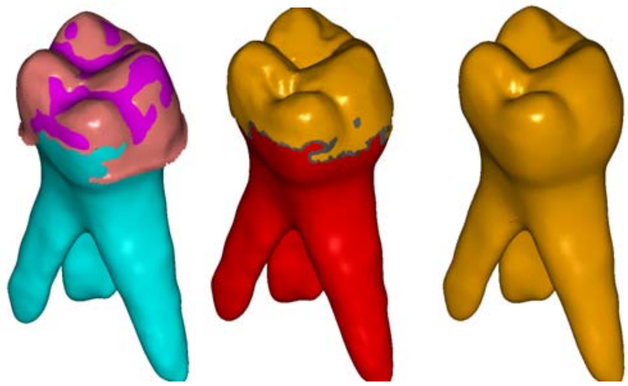
Having individual models created by optical scanning data of separate fragments of investigative dental arch and knowing their coordinates in general system of axes allows the creation of the whole dental arch occlusal surfaces' geometrical model.

3.1. Composition of tomographic and optical models

Using our original hybrid modeling methodology, special programs and algorithms, coordinates of points, describing elements of masticatory system, gained from computed tomography images were interconnected with optical scanning data of dental arches into one entirety, according to general system of axes.

The purpose of models composition procedure is to replace occlusal surface of tooth model, created by computed tomography scanning data with a more detailed occlusal surface model, based on optical scanning of gypsum model data. The main requirements for composition procedure are accuracy of occlusal surfaces' superposing and quality of connection in the contact zone. The following steps are necessary to perform during composition procedure of models, created by two different scanning system's data: (1) to superpose planes of occlusal surfaces of dental arches models, created by data of two scanning systems; (2) to superpose dental arches of both models; (3) to superpose occlusal surfaces of each individual tooth; (4) to replace occlusal surface of tomographic model with occlusal surface from optical model.

Global procedures of superposing two different scanning systems models do not cause problems because they are performed by modeling software. But final stage of composition procedure requires precision. Various versions of surfaces replacement are possible which differ in connection quality in the contact zone. Elementary variant is to "cut of" occlusal surface of tomographic model and "put on" it the higher accuracy occlusal surface of optical model. Final result in this case will depend on chosen level of "cutting of". Such methodology of models composition may be acceptable if only occlusal surfaces are involved in computations and cervical functional surfaces of teeth are not investigated in the biomechanical model. Higher quality of replacement of occlusal surfaces may be achieved by a more complicated composition procedure - after superposing of occlusal surfaces, intersections of surfaces which separate eliminated and reserved areas of the surfaces (Fig. 7) are traced.



a b c

Fig. 7 Superposed occlusal surfaces of both models (a); occlusal surface taken from optical model, other surfaces from tomographic model (b); finished composite smooth model of the molar tooth (c)

3.2. Optimization description of the models

Typical software designed for mechanics operate with relatively small size descriptions of the models. Various methods may be used to minimize model's descriptions, though it is necessary to keep suitably detailed occlusal surface, particularly in contact zones of occlusal surfaces. During minimization of surface describing data array the number of polygons on cervical area and roots of the tooth can be reduced signally (Fig. 8).

Full description model of the molar tooth is composed of 19636 polygons, reduced description model – of 5154 polygons. Height of the tooth is 22.24 mm, width – 12.97 mm and length – 14.22 mm. Area of the molar tooth model surface is 751.38 mm^2, volume of the model – 1035.26 mm^3. Average area of polygon is 0.038 mm^2.

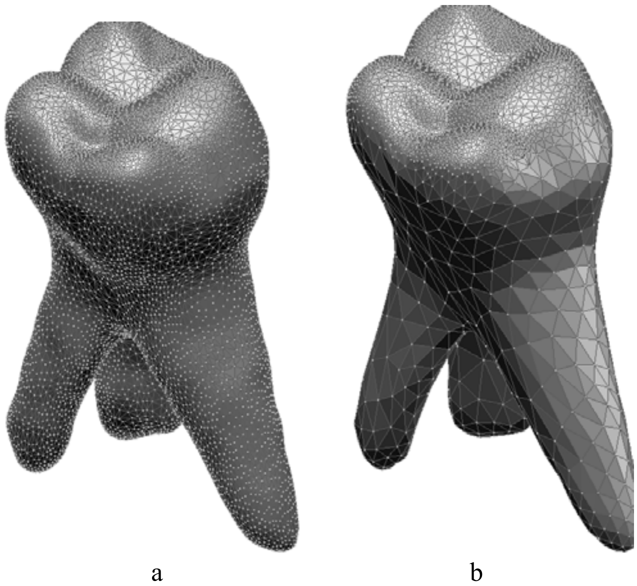


Fig. 8 Smooth models of the molar tooth covered with polygons: full description (a); reduced description of the cervical area and roots (b)

3.3. Formation of the geometrical model of the gypsum model of the whole dental arch

After fragmentary optical three dimensional scanning of the gypsum model of dental arch, geometrical models of each individual tooth are created and primarily processed. Then according to the general system of axes all of them are composed into solid geometrical model of the dental arch. Figs. 9 and 10 present models of the occlusal surfaces of the maxillary dental arches, Figs. 11 and 12 present models of the mandibular dental arches, created by the optical scanning of the gypsum models data. A little "skirt" around the every tooth shows the margin of the gingival surface. Surfaces of the cervical areas of teeth, perpendicular or negative to the occlusal plane are not presented in the pictures.

In the geometrical models of dental arches each tooth and gingivae are approached as separate objects. Each component of dental arch can have several variant of its model. Each variant of the component has its title, original coordinates of surfaces points – clouds, one

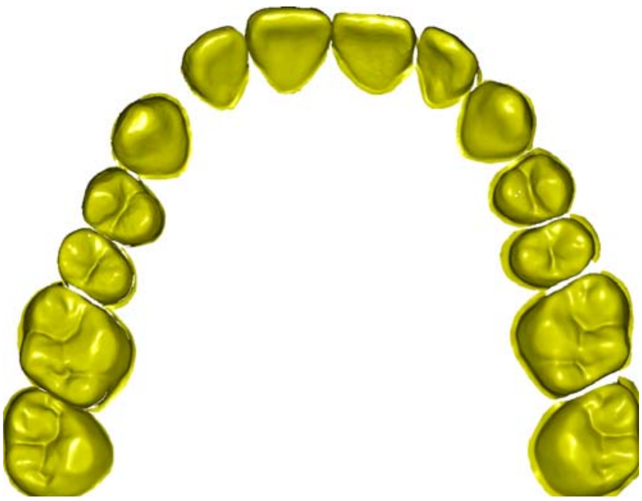


Fig. 9 Model of occlusal surfaces of the maxillary dental arch

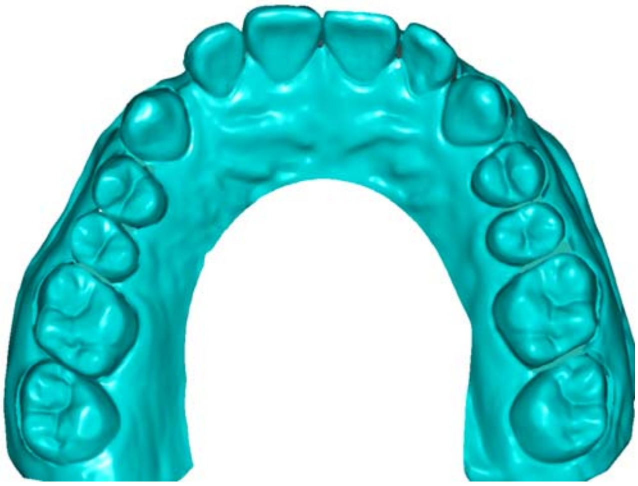


Fig. 10 Model of occlusal and gingival surfaces of the maxillary dental arch

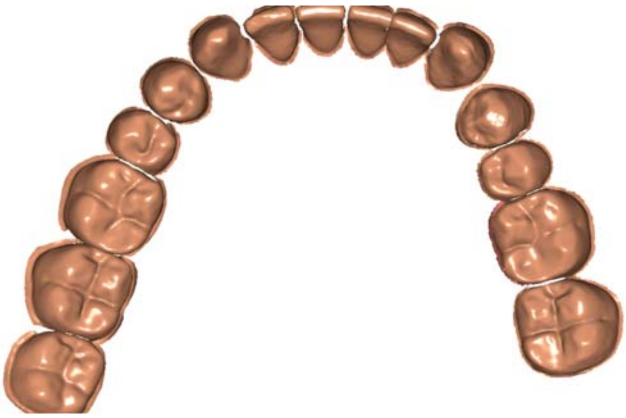


Fig. 11 Model of occlusal surfaces of the mandibular dental arch

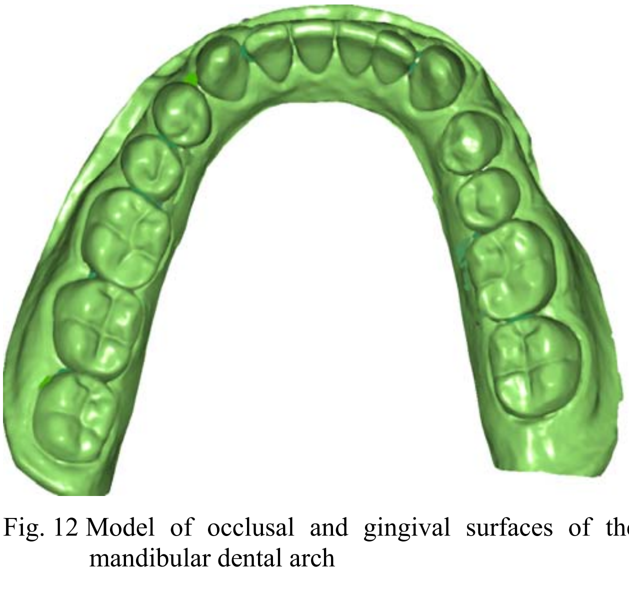


Fig. 12 Model of occlusal and gingival surfaces of the mandibular dental arch

or another procedure of primary processing, different procedure of data description minimization. Such descriptions of several variants of each component allow choosing the most appropriate variant for solving the particular problem during modeling of the masticatory system. One of the most relevant problems of mathematical modeling of such complicated system is how to combine rationally on the one hand - desirable high accuracy of reconstructed functional surfaces and on the other hand - to minimize data arrays to make them acceptable for contemporary modeling software and resources of personal computers. Of course, work stations may be used for solving the more complicated modeling problems.

5. Conclusions

A new method for the creation of three-dimensional geometrical model of the entire masticatory system of an investigative human being was presented in this article. Hybrid scanning methodology based on computed tomography and three-dimensional optical scanning enabled 2.7 times increment of teeth occlusal surfaces reconstruction without an increment of irradiance effective dose for the investigative person. The original hybrid modelling methodology based on data of two different scanning systems enabled creation of three-dimensional geometrical model of all hard parts of masticatory system characterized by high accuracy of surfaces geometry reconstruction and realistic spatial arrangement of system's elements defined by accurate three-dimensional coordinates. Created geometrical model of the main elements of masticatory system would enable the creation of high quality physical-computational model of masticatory system of a particular human being with possibility to investigate either each constituent part separately or entire system.

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NAUJA TIKSLESNIO ŽMOGAUS KRAMTYMO SISTEMOS TRIMAČIO GEOMETRINIO MODELIO SUDARYMO METODIKA

R e z i u m ė

Pagrindinė daugelio iki šiol sukurtų žmogaus kramtymo sistemos geometrinių modelių nepakankamo paviršių atkūrimo tikslumo priežastis – didelė apšvita, tenkanti tiriamajam kompiuterinės tomografijos skenavimo metu. Straipsnyje aprašyta originali modeliavimo metodika, paremta dviejų skirtingų skenavimo sistemų duomenimis. Šiame darbe kaulinių struktūrų ir dantų šaknų geometriniai parametrai nustatyti kompiuterinės tomografijos, o dantų kramtomųjų paviršių – trimačio optinio skenavimo metodu. Nustatyta, kad, taikant naują hibridinio skenavimo ir modeliavimo metodiką, minimalaus atkuriamo elemento dydis sumažėjo nuo 0.134×0.134 mm iki 0.05×0.05 mm, o efektinės apšvitos dozė sumažėjo nuo 3.78 msV iki 0.97 mSv, palyginti su tik kompiuterinės tomografijos skenavimo duomenimis paremta metodika. Taigi, naujoji metodika leido 2.7 karto padidinti dantų okliuzinių paviršių atkūrimo tikslumą bei išlaikyti tikrovišką sistemos sudedamųjų dalių erdvinį išsidėstymą, neviršijant tiriamajam leidžiamos apšvitos dozės.

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A NEW TECHNIQUE FOR CREATION OF A HIGHER ACCURACY 3D GEOMETRICAL MODEL OF THE HUMAN MASTICATORY SYSTEM

S u m m a r y

The main reason of insufficient accuracy of surfaces reconstruction in previously created models of the human masticatory system is high irradiance dose for the investigative person during the computed tomography scanning. This article presents original modeling technique based on the data of two different scanning systems. In this work geometrical parameters of the bony structures and roots of the teeth were estimated using computed tomography, and teeth occlusal surfaces were scanned with three-dimensional optical scanner. It was found that using new hybrid scanning and modeling technique the minimal area of reconstructed elements decreased from 0.134×0.134 to 0.05×0.05 mm and effective irradiance dose decreased from 3.78 to 0.97 mSv in comparison with the technique, based only on computed tomography scanning. Hence, the new technique enabled 2.7 times increment of teeth occlusal surfaces reconstruction and retention of realistic spatial arrangement of system's elements without an increment of irradiance effective dose for the investigative person.

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НОВАЯ МЕТОДИКА ДЛЯ СОЗДАНИЯ ТРЁХМЕРНОЙ ПОВЫШЕННОЙ ТОЧНОСТИ ГЕОМЕТРИЧЕСКОЙ МОДЕЛИ ЖЕВАТЕЛЬНОЙ СИСТЕМЫ ЧЕЛОВЕКА

Р е з ю м е

Главной причиной недостаточной точности реконструкции поверхностей до сих пор созданных геометрических моделей жевательной системы человека является большая доза облучения для исследуемого человека во время сканирования методом компьютерной томографии. В статье представлена оригинальная методика моделирования, основана на данных двух разных систем сканирования. В настоящей работе геометрические параметры костных тканей и корней зубов установлены сканированием методом компьютерной томографии, а окклюзионных поверхностей зубов – методом трёхмерного оптического сканирования. Было установлено, что применяя новую методику гибридного сканирования и моделирования, минимальная величина реконструированного элемента уменьшилась от 0.134×0.134 до 0.05×0.05 мм, а доза эффектного облучения снизилась от 3.78 до 0.97 мЗв в сравнении с методикой моделирования, основанной только на данных компьютерной томографии. Полученные результаты показали, что новая методика позволила в 2.7 раза увеличить точность реконструкции окклюзионных поверхностей зубов и сохранить реалистическое пространственное расположение составных частей жевательной системы, тем самым не превышая допустимую дозу облучения для исследуемого.

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