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Comparison of 3D scanned kidney stone model versus computer-generated models from medical images

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A B S T R A C T

With a goal to evaluate accuracy of kidney stone models created from medical images, comparison of computer-generated models against 3D scanned model is performed. Computer-generated models are made using 6 free and one commercial software for medical images obtained by computed tomography (CT) with a slice thickness of 5 mm. Digitized volume of the same kidney stone was obtained after its surgical removal and digitized using a contactless 3D scanner ATOS Compact Scan. Due to the complexity of kidney stone, the scanned reference model is not completely identical to real surgically removed stone from a patient. High maximum deviation is positioned mainly in the areas where the actual kidney stone is not scanned. The average surface deviation is in the range of 0.24354 mm to 0.44719 mm. Results reveals that the accuracy of the computer-generated models depends on quality of algorithms for tissue segmentation implemented in a particular software and on the skill of user. All software enabled us to create a 3D model of the kidney with clearly visible position of a kidney stone inside, accurate enough for planning the operation. It is possible to get a higher model accuracy by reducing the slice thickness during medical imaging; however, it increases the dose of radiation. Therefore, it is necessary to individually determine the optimum balance between the required quality of images and the amount of radiation that the patient is exposed to during recording.

A R T I C L E I N F O

Keywords:
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1. Introduction

Medical procedures like radiological diagnosis have become less invasive and more informative. 3D visualization and image processing plays an important role in radiological diagnostics and is of major importance for many clinical disciplines [1]. The ability to create models from medical images can be used in different ways. One of them is monitoring of growth or reduce anomalies and diseases of the body. Using the same parameters when creating the model from different time periods enables easy visualization of changes in the body, allowing doctors quickly and easily diagnose the patient's condition [2]. Generation of three-dimensional models from medical images in combination with rapid prototyping technology enables the production of individual specific model tissue as well as creating custom prosthesis in a simple and fast way [3]. The reconstructed 3D models can provide valuable medical information and powerful diagnostic tool for surgeons to understand the complex internal anatomy of the patient [4]. Shim, Gunay and Shimada in their scientific paper Three-dimensional shape reconstruction of abdominal aortic aneurysm came to conclusion that specific patient's three-dimensional model can be created with less than 5% deviation with the use of 15 CT images with a section distance of 5 mm. Such level of error is small enough for the purpose of medical diagnosis [5]. These models in combination with 3D scanning also can be use in some non-medical applications like forensic medicine, passenger safety and crash analysis [6]. In this paper we attempt to examine the efficacy and accuracy of different programs for generating 3D models from medical images. Models of kidney stone generated from medical images obtained by computerized tomography (CT) are individually compared to the reference model of kidney stone. The reference kidney stone was removed from a patient by surgery and scanned with high-precision contactless 3D scanner. For testing the accuracy, it is convenient to have a reference model. The kidney stone is very suitable since it can be recorded in high quality with medical devices, later physically removed and then measured. The kidney stone can be even visually compared with 3D printed model generated from medical images. Estimating the accuracy of the generated model provide helpful information in future approach to 3D segmentation of kidney area and in selection of software with enough capabilities.

2. Materials and methods

2.1 Inputs

Data that we used to create reference and computer model came from CT DICOM images of kidney stone but also from physically removed kidney stone from a patient. CT best images dense bones, which makes it very suitable for recording a kidney stone since stone density is mostly very similar to bone. It can be surgically removed and digitized in order to create a referent model for comparison with other models obtained from the computer generation of medical images. The necessary medical images for computer-generated models of kidney stones are made by standard abdominal two channels CT scan device Siemens Somatom Emotion 16 with a slice thickness of 5 mm. In order to create a reference digitalized volume for comparison, kidney stone had to be surgically removed from the patient's body.

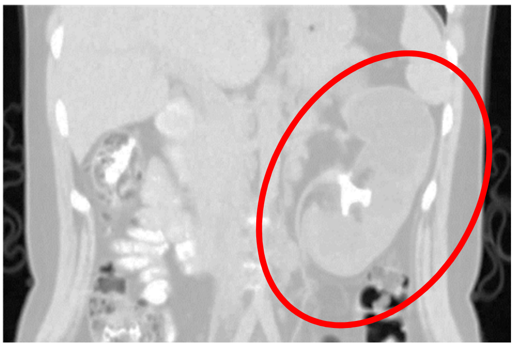

Fig. 1 CT section of the abdomen with highlighted region of kidney stone

2.2 3D Scanning

For digitizing volume of kidney stone non-contact 3D scanner, ATOS Compact Scan developed by GOM GmbH was used. It has one sensor head 340 × 130 × 230 mm dimension and supports measuring areas from 35 × 30 mm to 1000 × 750 mm, allowing fast scanning while still delivering high-quality measurement data. ATOS captures an objects full surface geometry and primitives precisely in a dense point cloud or polygon mesh with point spacing from 0.021 mm to 0.615 mm. It is widely utilized in various industries, and can measure different object sizes, surface finishes and shape complexities from 450 mm to 1200 mm working distance [7]. The system is fast, has an accuracy of up to 30 μm, but is very sensitive to glare brightness [8].

The reference model is made by scanning surgically removed kidney stone. The scanning process is composed of several steps such as devices and model preparation, the scanning and processing of the obtained values in the computer program [9]. Before the scanning process, for the more accurate results, the calibration of the system is performed. Calibration is done with the help of the calibration plate. The most important part of calibration plate are holes with larger diameter, which must be set in the view field of two cameras. The quality of the preparation directly affects the quality of the output. Optical scanner has problems to collect data points in holes of small diameter, what causes errors in the assessment of the position and diameter [10].

Selecting the best position for scanning is very important especially for complex cases such as kidney stones. Supports, which can be standard or individually designed for the needs of each scan, are often used to adjust the position of model. Sometimes it is necessary to scan the subject in many ways, and choose the best result [8].

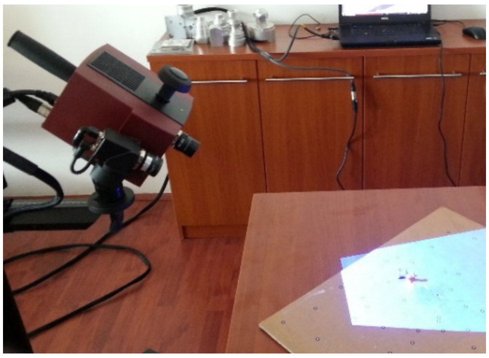

Fig. 2 Scanning kidney stone with ATOS Compact Scan

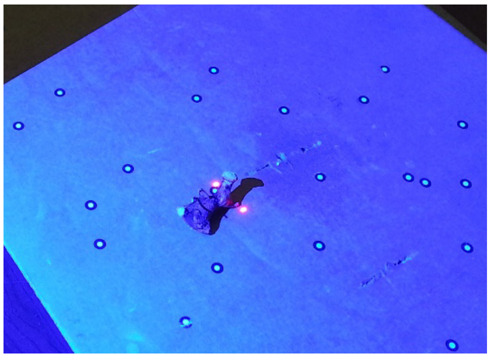

Fig. 3 Scanning a kidney stone

Fig. 2 and Fig. 3 show the way in which we recorded a kidney stone. Prior to scanning it is necessary to set the reference point. The reference points are self-adhesive labels applied to the object, support and work surface. It serves as a link between the individual subjects shooting at different angles. The reference points consist of white dots on a black background which allows them great contrast. The appearance of points, and the way they are set are also visible in presented figures.

After the object and equipment preparation, scanning is performed with the guidance of software support and manually moving the device around of the scanned object. The number of positions necessary for a full scan of the object depends on its complexity, and can amount to several times. According to Barbero B. R. and Ureta E.S. in their paper Comparative study of different digitization techniques and their accuracy, digitization on small pieces and those with sudden changes in their shape remains difficult in those parts that are visible but difficult to access. It is necessary to make several passes for their digitization, which considerably increases noise in the mesh [8]. After kidney stone is scanned, it is necessary to process the collected data. The program creates a mesh made of triangles from collected points which form a cloud. In ATOS Professional created model of kidney stone can be processed, and it is advisable to remove unnecessary parts of mesh model that is recorded by the scanner. Complete processing of object was performed in the program GOM Inspect V7.5 SR2 which is the manufacturer of the used scanner.

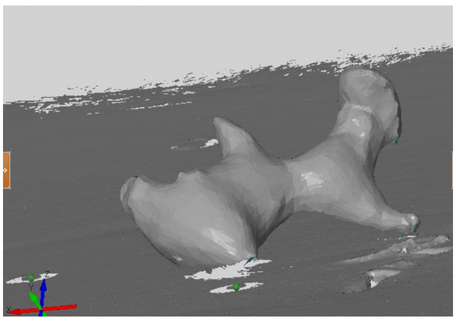

Fig. 4 Created model with all scanned parts

Fig. 4 shows the workspace of the program GOM Inspect and appearance of kidney stone model immediately after scanning. The model can have many unnecessary parts around such as supports and work surface, while at the same time there are places with missing parts.

Small stone size in combination with complex shape causes a lack of some part of information during the scanning so the referent model could not be closed completely. It takes a lot of skill and experience, to obtain usable model from such a scan.

2.3 Generating a model from medical images

To generate models from medical images requires the appropriate computer software designed for this purpose. There are a lot of available software used for medical purposes, some of them are very expensive and professional and some are free open source software. Software that were used in this work were professional 3D Doctor and 6 free open source software's: 3D Slicer, 3DIM Viewer, In Vesalius, ITK-SNAP, Mia Lite, OsiriX.

When generating models from medical images first we created the region of interest. Region of Interest – ROI is created due to the restriction of the area in the picture where we want to perform segmentation and allows us to create models only of the desired part. Segmentation is a function that automatically generates the contour of the desired object at all 2D images in which it is located. The threshold is an interactive tool, in the process of segmentation, which shows the desired object in medical images by setting upper and lower threshold brightness. Thus separates the object from the entire volume. Surface rendering is the creation of three-dimensional polygon mesh for the accurate representation of the model. A polygon mesh can be stored in different 3D formats such as IGES – Initial Graphics Exchange Specification and STL – Stereo lithography.

3D – Doctor 4.0

After loading DICOM files and previously reslice of images by one of the axes, interactive segmentation was performed. Reslice function provides visibility of certain features that would be difficult to see in the original format. Using these functions can override the limitations of the recording device. Results of the reslice function is reducing the cascade model and more accurate models. The models were created without and with the reslice function, with all other factors unchanged, in order to assess the manufacturer's claim that reslice function increases the accuracy of the model. Reslice function creates new cross sections with a much smaller slice thickness using a mathematical algorithm interpolation. Resliced image is stored on in the new image file TIFF – Tagged Image File Format. TIFF is a format for storing high-quality graphics and allows saving multiple images in a single file. After the original CT images were loaded into the program, there where available 106 sections, and only a very small number of sections where the kidney stone was visible. Reslice enabled segmentation to 511 images, and the slice thickness was reduced from 5 mm to 0.734 mm, Fig. 5.

After creating, the model is exported in STL format. The program offers a choice of types of STL files: ASCII STL or Binary STL. Due to its characteristics and advantages, the Binary STL format was selected.

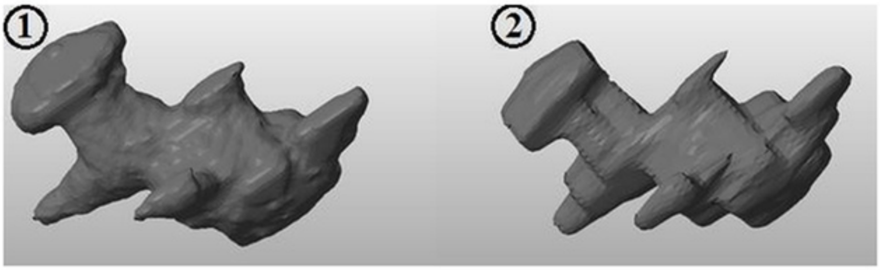

Fig. 5 3D Doctor - Left reslice model and right model without reslice function

3D SLICER 4.3.1

Module Welcome to Slicer is used to load medical images. To get the model from only a specific part of the image, it is necessary to cut the desired part. By inclusion the option ROI visibility, rectangle that indicates the part of the image that we want to maintain is set. The segmentation module requires Editor which has the tool Threshold Effect. The selected section will fill colour (green), and if the fulfilment of the section is poor it is necessary to change the boundaries to achieve the best possible fulfilment. After achieving satisfactory fulfilment, the module for creating the model is used. To create the model, we use the module Model Maker that can be called from the menu of modules or with previously used modules Editor.

Smooth option adjusts the smoothness of the model, but it affects the accuracy of the model and should be used with caution. When saving models, we cannot influence the quality and accuracy of the model, but it is possible to choose between several types of formats of 3D models such as VTK – Visualization Toolkit, PLY – Polygon File Format and STL, Fig. 6.

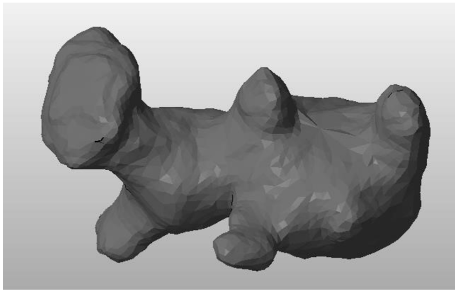

Fig. 6 Created model in 3D Slicer

3DimViewer 2.0

After loading DICOM files, the program automatically offers the possibility to create region of interest (ROI). The best way for segmentation is setting the threshold. Tool for setting the threshold is available without licensing additional segmentation plugins. The tool has the ability to choose the lowest level of brightness in the picture and the highest new brightness to form the model. Clicking on the edge part of kidney stone lower threshold is set while the upper is possible to leave the maximum value. Segmentation is done with command Perform Thresholding and segmented parts are painted red. Following command Upgrade Model Creation was used to create the model, by which the model is smoothed. The model obtained from current command Create Surface Model gave poor results because the model is very sharp, Fig. 7. To obtain a more accurate model the most important parameters are properly adjusted Smoothing and lower threshold brightness. When saving model, there is no possibility of further quality adjustment and selecting the type of format. The model can be saved only in the STL format. For the purposes of this study we used only publicly available commands. For better results it is advisable to buy additional modules for segmentation.

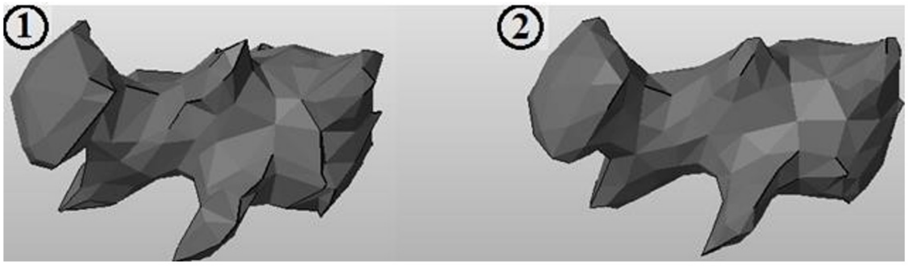

Fig. 7 Left model without upgrading and right model with upgrade Model Creation

In Vesalius 3.0 – Beta

Tools in the program are arranged in the order that is destined to create the model. After downloading the file, user needs to set option Threshold. The program offers already defined boundaries for tissues such as bones, skin and muscles, but also offers manual control. In our example, manual setting of the boundaries was used. After viewing all the sections and detailed adjustment of threshold, model was created using the command Create surface. Because the area of interest is not marked, a created model contains all other bones beside the kidney stone. The program offers several possibilities for separation: selection of largest separated area, manually selection one of the separated area, automatic separation of all separated areas and creation of separate model for each individual part. The manual selection of the separated area is selected because the kidney stone is not the largest separated area. Automatic separation of the all surfaces is not suitable because program will create model for all bones and other parts that has similar density to kidney stone. By running tools Select regions of interest and clicking on the kidney stone in the window, kidney was separated and a new model is automatically created, Fig. 8. Saving to the computer is possible in several types of formats.

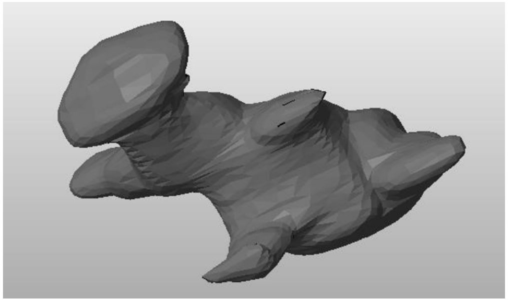

Fig. 8 The created model with In Vesalius software

ITK Snap 2.4.0

After loading the medical images, in the menu Main Toolbox the Snake ROI tool is selected. It uses interactive rectangles and allows accurate adjustment region of interest in all respects. After adjustment of the rectangle, in the Tool Options menu Segment 3D tool is selected. It initiates a process of automatic segmentation of the project that includes only part of the image selected by region of interest.

After determining the region of interest, it is necessary to process the image, in other words to separate the desired element from the rest of the image. The program works on the principle of developing a balloon from the circle to the contour that represents a kidney stone in a particular section. Spreading the contours is defined by a mathematical formula at every point, and parameters of the equation depend on the parameters of the spread curve (Snake parameters). It is necessary to set up as many balloons in the inside area of kidney stone. After setting of all parameters, begins the process of spreading balloons and creating contour that eventually form a model. Large number of iterations is carried out, and a way of creating a model is visible in steps, Fig. 9. Saving model is possible in a number of different formats of 3D models such as VTK, STL and BYU.

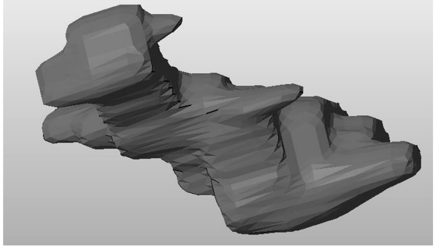

Fig. 9 Created model with ITK Snap software

Mia Lite 2.1

Adjusting smoothness of the model is done with the Smoothing Factor option. With the small changes of Smoothing Factor, a great impact on the accuracy of the model is visible, Fig. 10. On the kidney stone that is created with a very small factor of smoothness of 0.11 a large cascade of model is visible, while stone with the smoothness factor of 0.3 loses one of his parts. Therefore, it is necessary to use this factor very carefully.

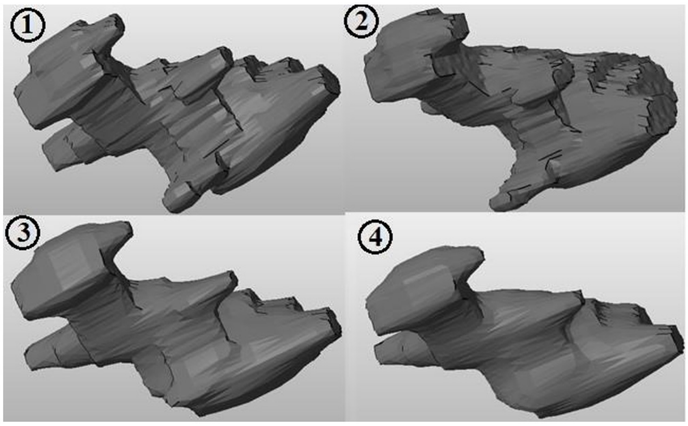

Fig. 10 Influence of smoothness factors on the model: 1) Smoothing factor 0.11; 2) Smoothing factor 0.15; 3) Smoothing factor 0.3; 4) Smoothing factor 0.42

OsiriX 5.6

After loading the medical images, tool for segmentation Grown Regions (2D / 3D Segmentation) is started. The tool includes several algorithms for segmentation. Before making a model, it is necessary to change the pixel values outside the area of interest, so that the created model is limited to the desired area, Fig. 11. This would suggest deletion of all the rest of the image and sections that do not contain created area of interest. Tool used for changing the pixel values was Set Pixel Values to. The brightness level of all pixels outside the ROI is set to the value -1024 which represents the absolute black level of brightness. Software perceived that as a void.

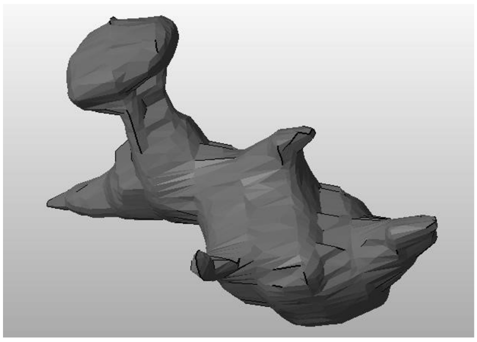

Fig. 11 The model created in OsiriX in the Microsoft Windows environment

2.4 Comparison in GOM inspect

For comparison of the scanned kidney stone and models obtained from medical images, a computer program GOM Inspect V7.5 SR2 is used. GOM Inspect is a free computer program developed by GOM GmbH. In addition to serving as a computer support for 3D scanning process, it has the ability to repair the scanned model, to measure it and to compare scanned model with other models. Due to the complex shape and size of the kidney stone there are some differences between the scan and the actual model that should be taken into account when considering the results of the comparison. In GOM Inspect scanned models have a name Actual Elements and they are shown in grey colour, while all other elements subsequently imported into the program are marked as Nominal Elements and shown in blue colours, Fig. 12. Before comparing the actual and nominal elements, alignment of elements is executed. Alignment can be divided into pre-alignment and main settlement. Each alignment has several methods that can be selected depending on the needs. Tool for pre-alignment contains several options.

Option CAD allows selection of nominal elements, while option Actual mesh selects the actual elements that will go into the process of alignment. After aligning, the models were analysed with tools for inspection, and reports were created. Search time allows to select a time for calculating the alignment. To place the elements in proper form we can use additional help point function and set a several points on the same positions on real and nominal element. Using the function Compute additional best fit, software calculates the best position for precise alignment. After the pre-alignment, software provides information on the average deviation surface of models. This deviation depends on the performance of tools for alignment, and is not the reference data about the overall accuracy of the model. Because the model has very complex shape the main alignment cannot be ascertained, i.e. it does not contribute to better alignment. The only possible inspection of model is a surface deviation between the real and the nominal model.

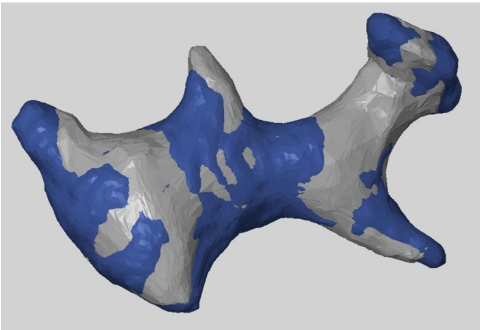

Fig. 12 Aligned Actual element (scanned model) in grey color and Nominal element (imported model) in blue

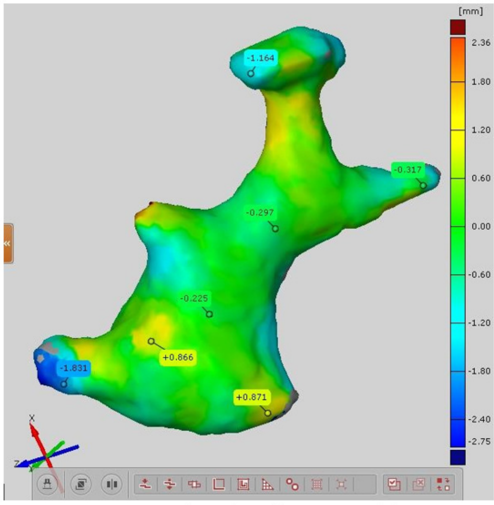

Fig. 13 Deviation with specific values

The function Separate surface comparison per CAD group allows the separation of deviations inspection for each loaded nominal model. The function Actual mesh selects the actual elements that will enter the inspection process. With the parameter Max. distance determines the maximum distance between the points of real and nominal element that will be taken into account. All deviations greater than the maximum distance parameters are not taken into account and they will be indicated in grey on visual display. Tool for inspection of area deviation displays the results in visual form on the silhouette of the nominal model and the range of colours shows the deviation values. Positive values indicate the nominal model surface that is below the surface of the real model, while negative values indicate the nominal model of the surface that is above the actual model. The grey colour indicates the area that is not compared because of the lack of the part of real model.

Tool Deviation Label sets points on a visual representation of where we want to know exactly the amount of deviation. Fig. 13 shows a visual representation of the variation in several points with specific values in millimetres.

3. Results and discussion

To bring the conclusions, we analyse several parameters for each software used in this paper, Table 1. For better visibility, the test results are grouped in Tables 2 and 3. Software showed that despite the simplicity of generating model, setting threshold and smoothness has the major impact on model accuracy. For exact model the parameters of the lower threshold and Smoothness option factors needs to be set, but each parameter has a very large impact on the model and is difficult to coordinate them. The lower threshold level gives a more accurate model of the shape but increases the model dimensions and make him very cascade. A smoothness factor has a significant impact on model shape. Even small increase of the smoothness factor removes parts of the model. The picture shows the influence of smoothness factor on model shape with a constant parameter of the lower threshold of brightness that is 140.

Model 3 from Fig. 14 was selected as the most accurate because it contains all the parts of the kidney stone although GOM Inspect is not rated it as a model with the lowest average deviation of surface. The results of comparison with OsiriX software show satisfactory deviation on large area of the model, except where the program created a dent deeper than 8 mm. Visual inspection reveals mathematical nature of the dent and that it occurred during the interpolation while model was generated. The largest surface area difference between the used software's is 8.16 cm^2, largest model volume difference is 2.02 cm^3. Maximum deviation above the surface of the real model is 9.983 mm (3D-Doctor) and 8.457 mm under the actual model (MiaLite).

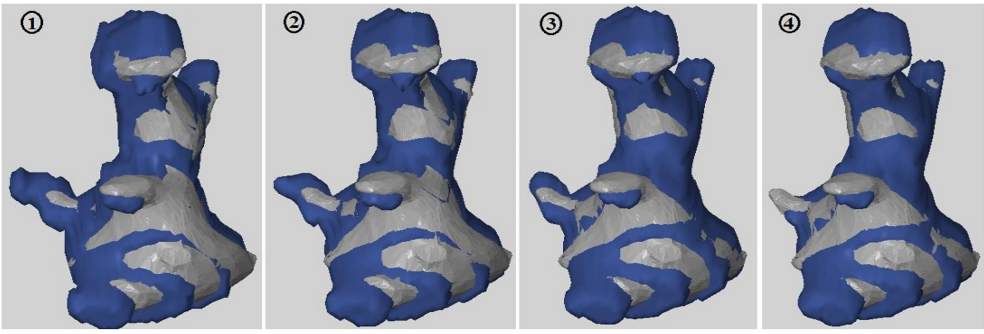

Fig. 14 Models obtained by software Mia Lite – 1) Smoothing factor 0.5; 2) Smoothing factor 0.1; 3) Smoothing factor 0.12; 4) Smoothing factor 0.15

Table 1 Result comparison of the surface area, volume and deviation for all models

Software name	Surface area (cm^2)	Model volume (cm^3)	The average surface deviation (mm)	The maximum deviation of the area under the actual model (mm)	Maximum deviation above the surface of the real model (mm)
3D-Doctor	20.67	4.68	0.24354	7.583	9.983
Slicer	22.20	5.56	0.43737	3.303	9.953
3DimViewer	24.23	5.51	0.29845	3.350	6.751
InVesalius	21.22	4.92	0.24515	2.359	9.480
ITK-SNAP	25.85	6.35	0.44607	8.039	9.612
MiaLite	28.83	6.70	0.44719	8.457	8.086
OsiriX	22.53	5.00	0.25507	2.387	8.483

Table 2 Results for 3D-Doctor, Slicer and 3Dim Viewer software

Software	3D-Doctor		Slicer	3DimViewer
	With Reslice	Without Reslice		
Length / width / model height [mm]	33.69/29.32/40.83	33.33/28.92/39.84	32.52/32.04/29.50	34.37/31.68/44.67
Volume of model (cm^3)	4.68	4.49	5.56	5.51
Surface area (cm^2)	20.67	21.34	22.20	24.23
Number of triangles	11556	4408	3074	1174
Used segmentation	Interactive Segment...	Interactive Segment...	Module: Editor; Option: Threshold Effect	Automatic Segmentation
The lower limit of brightness	1458	1458	300	280
Smoothness factor	no	no	10	4
Additional options / parameters	Used Option: Reslice	no	no	no
The average surface deviation (mm)	0.24354	0.33978	0.43737	0.29845
The maximum deviation of the area under the actual model (mm)	7.583	8.285	3.303	3.350
Maximum deviation above the surface of the real model (mm)	9.983	9.158	9.953	6.751

Table 3 Results for In Vesalius, ITK SNAP, Mia Lite, Osir X

Software	In Vesalius	ITK-SNAP	MiaLite		OsiriX
			MiaLite - selected	MiaLite – minDev	
Length / width / model height (mm)	33.44/29.85/41.26	33.34/30.48/45.00	33.81/30.80/44.98	32.98/29.32/44.89	31.12/43.42/34.05
Volume of model (cm³)	4.92	6.35	6.70	4.49	5.00
Surface area (cm²)	21.22	25.85	28.83	21.65	22.53
Number of triangles	2425	4672	5076	4000	4354
Used segmentation	Manual threshold	Intensity regions	Threshold	Threshold	Threshold (lower/upper bounds)
The lower limit of brightness	400	158	140	1458	100
Smoothness factor	no	3.55	0.12	0.10	30
Additional options / parameters	no	Balloon force: 0.9 Curvature force: 0.26	no	no	Resolution: 100 % Decimate: 0.1
The average surface deviation (mm)	0.24515	0.44607	0.44719	0.30702	0.25507
The maximum deviation of the area under the actual model (mm)	2.359	8.039	8.457	9.262	2.387
Maximum deviation above the surface of the real model (mm)	9.480	9.612	9.998	8.086	8.483

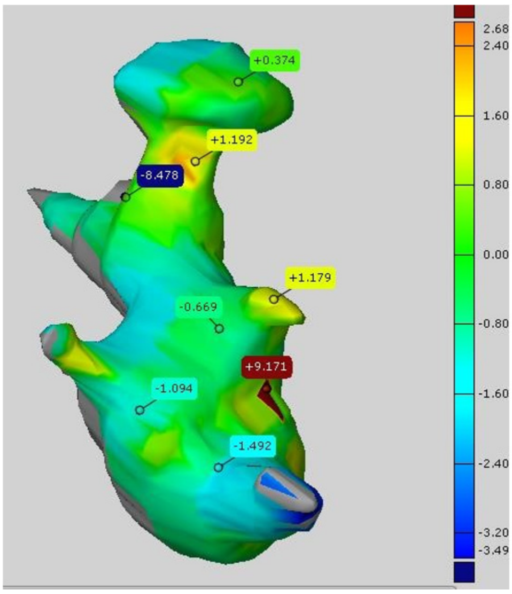

Fig. 15 Surface matching of nominal and real model on the dent area

4. Conclusion

Determination of the most accurate computer generated model is very challenging task, because beside numerical values the deviations of models should be also visually inspected. Shape of the computer-generated models must be compared with the actual kidney stone shape to decide which deviation can be ignored. Additive technologies like 3D printing, which are nowadays more and more in the application, provide the possibility of 3D printing generated models in order to make the visual comparison. 3D printed models obtained from medical imaging are useful when planning surgical procedures. Analysis of the results showed that the software for generating models from medical images could get models with acceptable accuracy for planning medical procedures. High maximum deviation, above and below the surface of the real model, are positioned mainly in the areas where the actual kidney stone is not scanned because of his small size, complex shape and limitations of Atos scanning device. Deviation occurs because of the inability of computer program GOM Inspect to determine which part of the model surface belongs to not scanned part of the kidney stone. Not all used programs have the ability for processing and precise joining of medical images obtained from multiple directions. 3D-Doctor is the only used software that has the ability to manually merge images from different directions. We can assume that specific algorithm for merging images from multiple directions would increase the accuracy of the resulting model. In a future research we have considered the development of an interpolation algorithm from several sections directions. Created algorithm will be used for an error analysis after automatically merging images from axial, sagittal and coronal plane.

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